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BROADCAST CONTROL OF AIR TRAFFIC

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I. INTRODUCTION

In comparing our oldest form of long-range transportation, ships at sea, with aviation, we note several interesting facts. The marine concepts of traffic control are almost all self-contained on the ship with little central control authority being accepted from the shore. This marine concept stems probably from the fact that shipping as a form of transportation has been successfully employed for hundreds of years, reinforcing the early concept of the full authority of "master of the ship" in all matters, including avoiding collisions with other ships and objects.

Aviation, however, being only about sixty years old, and then perhaps only significant in the last thirty years, has accepted many innovations and technologies rejected by the marine experts. Consequently, aviation is in many respects far more advanced. The current marine collision rates are appalling, so much so that the alarm has been sounded in the science of marine navigation, and traffic control attempts are being made to establish some new means of reducing the obviously excessive losses in collisions and groundings, particularly in restricted waters such as harbors (reference 1).

Aviation, of course, has the third dimension, vertical separation, which has done more to hold its accident rates to lower values than marine rates (for example, air carriers compared with major ships). Vertical separation has avoided many cases that would have been collisions in two dimensions. Anyone who suggests that ATC gets all the credit is unwilling to admit this pure chance advantage of aviation. It can, therefore, be concluded that if ATC were all conducted at the exact same elevation, it is possible that air collision rates (collisions with other aircraft and objects) would equal or exceed the appalling marine rates. Psychological factors (fear of flying) and the higher probability of fatalities in any aviation accident further stress the differences.

Consequently, aviation has become mostly a system of highly centralized ground control with "radar vectoring" being

the major tool in any dense traffic region. Of course, radar vectoring also exploits vertical separation to the maximum, using an air pressure gauge known as the barometric "altimeter" to achieve height differentials. This traffic concept has tended to create electronic means for the (ground-based) air controller that are much more accurate than the means used by the pilot for normal navigation of airways. A study of FAA documents (1) AC 90-45 and (2) AC 91-30, which briefly describe (1) the VORTAC Area-Nav concepts and (2) the radar vectoring concepts using the national SSR (radar system), clearly shows that the ground surveillance data available only to the ground controller of air traffic is about 10 to 20 times more accurate than the pilot's navigation and track information. The pilot's information is basically derived from airborne R-Nav and VORTAC instruments, and the data is displayed to the pilot in the cockpit.

Thus, we see the pilot being "vectored"--continuously steered--in many cases through a maze of other traffic by personnel viewing a radar scope on the ground. An increased emphasis on radar vectoring or its equivalent is proposed by some authorities. An obvious risk exists in several major areas if this trend continues. Failure of the SSR is one. Conflict between the R-Nav displayed track (to the pilot) and the ground SSR track display is another. The pilot and controller may not be viewing the track situation the same way, creating potential violations of separation criteria. "We obviously cannot continue to let one man on the ground navigate more and more aircraft without eventually getting into trouble" (reference 1). We must find an optimum means to provide the pilot with better information on where he is and where he intends to be than he presently has available. Accuracy, flexibility, economics, coverage, uniformity of data, and quality of data all must be considered, optimizing each in a total-system approach. VORTAC is deficient in too many of these areas when applied to wide-area navigation concepts.

In the marine case, experts say it is obvious that some centralized shore authority must be added in the dense traffic areas, such as ports and narrow waterways, where many ships converge and move on regular schedules including fog conditions.

Thus, in both our most ancient form of transportation (marine) and in our most recent form of transportation (air), we find the two generalized concepts of (1) centralized control (ground or shore), and (2) captain or on-board control being examined. In the marine case, after centuries we are now considering changing major rules and concepts, including adding extensive electronics guidance and control to achieve a more centralized control.

In the air we have probably overemphasized centralized control (ground computers, ground radar, radar vectoring). Consequently, we are now looking at means for bringing the pilot back into more participation in the act of traffic control (such as his own speed, destination, track keeping, separation, etc.). This concept will cause the controller to provide more of a surveillance function, rather than a navigation function, by avoiding extensive radar vectoring. This new balanced concept is herein called Broadcast Control of air traffic.

ICAO (International Civil Aviation Organization) recently established a panel on this subject known as the panel on Revision of General Conception of Separation (RGCS). A good summary of its activities is to say that it will re-examine the relationship of the pilot and controller in navigation, separation, etc., in our modern dense air traffic environments as well as other categories: (1) ocean, (2) medium, (3) high density, and (4) very high density (areas).

Two phrases used herein will be: Close Control and Broadcast Control to differentiate between the two ATC concepts. Close Control assumes that the present techniques are expanded--that is, the ground (computers-controller) will control (closely) each aircraft individually using radar vectoring as the primary ATC technique with the pilot employing R-Nav as a minimal secondary need in terminal areas. Broadcast Control assumes that a new balance of equality between improved cockpit guidance and control capability and ground control is implemented so that the pilot will be an equal participant in following track (more accurately than at present), maintaining desired track speed, maintaining air-to-air common track separation, and meeting scheduled destination (time-position), etc., goals far better than the pilot is now capable

of achieving in terminal areas because of the VORTAC deficiencies. This in no way downgrades the full radar ground system (SSR) for surveillance, schedule planning, and assuring the pilot that he is safe by being monitored continuously and that he is executing the ATC required conditions in dense traffic--all with more pilot participation than in the past. It is a means of preventing an overload (and potential failure through delays, complexity, etc.) of the use of our surveillance system by placing the navigation and other functions in the air, using a new coordinate system suited for such purposes.

We do not in any way infer that Broadcast Control is a "free-lance" operation of the pilot as in the marine case, since this would have disastrous results. However, we do mean that Broadcast Control is a new concept of ATC wherein we wish to achieve the optimum balance between the ground radar system and the precision (improved) coordinate Area-Nav system (LF-VLF). We seek in Broadcast Control the optimum <u>balance of authority</u> between the pilot and the controller; we also seek an ATC concept suitable to very-high-density ATC as well as very-low-density ATC. We also seek in Broadcast Control a means of cost benefits to all users including general aviation, military, and air carriers. Broadcast Control should offer major improvements in capacity while simultaneously creating major reductions in the cost of ATC.

Some of the fine gradations between Close and Broadcast Control of air traffic are not always obvious; however, one purpose of this study is to clarify and refine the definition of Broadcast Control. Goals that are significant to aeronautics include increased capacity of our airports and airways, with reduced risk of collisions with the ground or other aircraft. A further goal of Broadcast Control is to take the insurmountable load (that is increasing) from the (centralized, radar-tracking) controller system so that it can survive and serve ATC by doing the ATC jobs <u>it does best</u> in an improved manner, instead of diverting its capacity to functions (such as navigation of aircraft) that are done better by other means. The ground monitoring and planning of control and separation of dense traffic remains an enormous burden.

Major changes in the pilot's ATC functions, economics, numbers of ground personnel, use of SSR data, etc., are all involved in this change of emphasis from Close to Broadcast Control. These changes, which are evolutionary and not revolutionary, are compatible with our current national investment in ATC and will be identified in more detail than in the initial "overview" study of this subject in "Aeronautics and Air Traffic Control" (reference 10). These ATC involvements of the pilot, his displays, his ability to refine the flight control of his aircraft (better track, altitude, track speed, air-to-air separation controls, etc.) are primarily problems in aeronautics, although electronic sensing of the data is obviously essential.

However, until we really comprehend (1) what Broadcast Control means, (2) how the pilot really participates in ATC functions (rather than being a lackey to the controller or computer), and (3) how the pilot-controller relationship varies in different air traffic densities, we cannot define in the necessary detail an aeronautics program that is required to evolve ATC toward the improvements that are obviously possible with Broadcast Control. Such obvious improvements as being able to fly curved approach paths precisely defined in three coordinates, at exact track speeds (not airspeed), yet to a tolerance at the runway threshold of about ± 5 seconds are but a few of the many examples of what is primarily an aeronautics constraint on the future of ATC as well as the future value of aviation. Until we can find means to do these and many similar things at lower costs for these new capabilities and with higher safety, then ATC will remain the constraint to the future public value of all of aviation. It is increasingly evident that these constraints are aeronautical and pilot oriented rather than electronic. Since we know electronics can provide the essential inputs once defined, the problem is to define them in terms of Broadcast Control. However, the electronic inputs to the aircraft and pilot (such as R-Nav) must be much better than the current VORTAC system can provide.

II. CONCEPTS OF INCREASED PILOT PARTICIPATION IN ATC

Recently several investigators and planners of future ATC systems and concepts have suggested more pilot participation in the ATC control loop. For example, the International Civil Aviation Organization publication of August 1971 was devoted to various international views on ATC, one article noting that: "This thinking is in favor of placing more responsibility for the ATC process, particularly the separation part of it, in the aircraft cockpit, and in this way relegating ATC (ground control) to traffic directions along ATS routes, at intersections and at airport runways."--"Any look into the future must be based on the reality of today, where we find the greatest difficulty centering on the human controller in the system." An MIT report notes: "By tightening the control loop over aircraft separations through including the pilot as a monitor and active control agent, it would seem to be possible to demonstrate reduced standards at higher levels of safety . . ." The DOT-ATCAC report (reference 7) discusses the use of Strategic Control some time in the future--a concept also involving more pilot and cockpit responsibility in ATC functions.

However, the means for accomplishing these ATC functions in the cockpit vary with different technical proposals. In the concept of an Intermittent Positive Control system (IPC), a new data link is essential to provide detailed but standardized messages to the pilot from the ground surveillance system, addressed and transmitted automatically to individual pilots. In another concept, the SSR system uses a new digital data link (differing from the IPC link) to create a cathode-ray display of traffic for the pilot much like the controller's display, but with filtered information. By using the SSR codes, only pertinent traffic need be viewed by the pilot in his display for his maintenance of spacing, etc.

In even another future ATC concept we see the overall, detailed programming of the many traffic movements planned adequately in advance so that routings, track directions, velocities,

etc., are transmitted in one message to the pilot much like a flight plan. The three-dimensional and time coordinates are based on a more uniform grid of common coordinates possibly supplied by a wide-base LF/VLF system. Such coordinates are sensed directly in each aircraft executing its individual plan.

In this latter case, the pilot may actually file and request the flight plan in these coordinates, and it will be approved (possibly with minor modifications to interface with all other flight plans at that time), so that he knows well in advance his detailed operational ATC plan, and few if any minute-by-minute decisions have to be made by the ground. Essentially, radar vectoring is avoided, but the SSR capacity is applied to monitoring the total ATC scheme, leaving detailed ATC functions (speed, spacing, etc.) to each pilot.

Thus, we see that much of the conceptual thinking about the future of ATC is now turning toward obtaining much needed assistance from the pilot, his displays, and his ability to precisely affect the flight properties of his aircraft in all axes to aid in the ATC process. This should distribute the ATC load, avoiding what may become an unmanageable controller-computer load if the pilot participation and responsibility is not engineered into the ATC system. This is the goal of Broadcast Control.

One of the ICAO articles raises serious questions and doubts about increased automation of the ATC decision process to a point where even the human ground controller cannot take over if the computerized commands somehow fail or go astray. A given degree of ground automation will be essential, but the improved ATC pilot participation and his new relationship to the controller must be considered the direction for the future. The total ATC burden is then borne by the two parties, each carrying the load that he can affect the most and each with the responsibility of most concern to him.

Although the IPC concept is a means to this end, it is but one option with a risk that may not warrant the investment. In the IPC concept, the ground surveillance system is further burdened and relied upon to determine when proximity pair spacings

become dangerous. This data is then transmitted (only ground-derived) automatically on an automatic uplink (or data link) to the specific pilots involved, giving each or both pilots commands to which there is no alternative but to blindly obey. Some collision avoidance systems operating independently of the SSR system also adopt this blind pilot command idea, merely commanding the pilot (without question) to climb or descend. His judgment often does not enter into this mandatory maneuver.

Neither of these concepts of commanding maneuvers is likely to be accepted when one really understands the pilot and his responsibilities--both real and legal. Furthermore, a serious question arises when an electronic command occurs that the controller may not concur in--that is, in fact a "false-alarm"--resulting in traffic disruption or chaos. These concepts are often the solutions of "electronic enthusiasts" who have little awareness of the contributions the pilot can make and should make. Many electronic enthusiasts are also overly confident as to what electronics can deliver in the "real world" in the form of a safe high-integrity system that can safely control several dozens of aircraft, each with 400 lives at stake.

A. BROADCAST CONTROL INVOLVES PILOT SKILLS, JUDGMENT, AND RESPONSIBILITY

A Broadcast Control concept of ATC is discussed here that provides the desired pilot participation (which now seems to be the direction of the future of ATC). This concept involves the pilot in a redundant manner, does not overburden the SSR system (as in IPC), but does recognize SSR as the foundation of ATC surveillance (but not navigation or track guidance). An independent collision avoidance system that is not a part of SSR does not seem necessary, because the SSR will supply this function now that it has been relieved of the other functions.

We have the ability with modern computers to plan non-conflicting traffic flow in three dimensions in dense-traffic airspace. The flight path and schedule planning must be done correctly, and the pilot must be given the ability to actually execute his specific plan. Today the anticipatory flight track planning

cannot adequately occur for many reasons, one being the deficiencies of the track-forming system itself (limitations of contiguous coordinates, poor coordinate geometrics, signal coverage, accuracy, etc.). Further, we do not use the concept that ground ATC is basically a planning, monitoring-surveillance function rather than an instant-by-instant decision making and guidance system. The latter capacity has been forcibly developed since the SSR (radar transponder) system is about 20 times better than VORTAC. Given a new track and coordinate system equal to SSR quality, we can plan the flight, in these new coordinates, and approve them after a computer has scanned all flights in a given volume of airspace and modified and approved them prior to their actual use. The pilot, having a 20 times improvement, can now execute track and schedule if the proper aeronautics exist in the form of displays, flight controls, maneuverability, etc.

This Broadcast Control concept avoids the unexpected overloading of controllers that now occurs, resulting in long delays caused by "ad-hoc" planning and decision making by a controller, usually uncoordinated with other controllers doing the same thing. The current traffic planning stage is not adequate and does not include pilot participation in ATC for maintenance of spacing, track speed control, track following, and other functions that he can perform better and with much less delay than the ground controllers (or for that matter the ground computers fed by the surveillance data, digested and relayed second-hand to the pilot by a data link).

In Broadcast Control concepts the pilot, upon sensing the track (track deviation displays), adjusts his speed to provide the rate of track motion as per the ATC plan. The ground monitors these basic pilot ATC functions, carefully notes future intersections for common airspace occupancy to be sure that aircraft will be separated in time as the flight plan computer has determined. The plan "broadcasts" to pilots in advance, and each uses the broadcast data and broadcast coordinates of his immediate concern to comply with the overall scheme. Codification of an area could result in a simple voice message from the ground, establishing the

entire sequence, since most flight plans are only slight variations of previously used plans.

In the ideal case (not realistic but to exaggerate the impact of Broadcast Control on ATC), the pilot would, upon receipt of his validated flight plan, take off and guide his aircraft on a precision, geometrically varying track in three dimensions. His track speed would be indicated by the plan in terms of the track coordinates (such as a wide-area navigation system with a uniform grid of constant positional accuracy). The pilot would proceed to his destination within the time limits and land without ground control intervention. However, during this scenario of the perfect flight in dense traffic, the ground is monitoring in depth his every action to determine the deviations from track and track speed or check points to assure that no conflicts (and certainly no collisions) will occur because of poor pilot execution of the specified and planned flight track schedule parameters. The pilot is now in his own right and contributing to ATC; he is not being "vectored" instant-by-instant in a nearly "open loop" fashion as so often occurs today, resulting in the enormous burden, stress, and overload of air traffic controllers. The present "ad-hoc" solution to peak traffic problems must be abandoned, because the impact or chain reactions that occur from instant to instant (local decisions) in the total system cannot be predicted. There is a growing need to organize the traffic flow ahead of time and use pilot functions in ATC so that the radar controllers can function without the constant risk of being overloaded. One must have an organized flight plan, based on a uniform set of contiguous national coordinates that are uniform and equal in accuracy to the ground surveillance system (VORTAC does not have these required characteristics). An LF/VLF system of uniform coordinates should be seriously considered and tested for a new national ATC-Navigation grid, using perhaps four to six large transmitting stations in a complementary manner with the VORTAC network, which is then operating at a lesser level but in an active partnership with an LF/VLF system. VORTAC and LF/VLF (wide Area-Nav) complement each other when engineered together for transition to provide this new

Broadcast Control concept. To put this concept in different terms, the pilot cannot participate adequately in the ATC system today without the use of precise Broadcast data. Such data is now available on the ground. The SSR transponder system is providing this, but is already overloaded in support of the ground controller and computers. To relay this ground SSR data to the pilot in place of a direct attack on the real problem is to further dangerously overload the SSR system. A fully complementary, pilot-oriented, guidance system engineered directly for the requirements of the pilot's participation in Broadcast Control is now warranted.

Admittedly, much research is needed on many aspects of the pilot-participation-in-ATC concepts that are now becoming popular. First, the pilot must be catered to in the system design as a knowledgeable and cooperative individual, not a lackey to dive or climb at the whim of some electronic black box. This means the presentation of all ATC-related information to him in a form that builds his confidence in it, and that will give him adequate information to exercise his judgment and decision process within the bounds defined by our concept of "ATC Broadcast Control." He does not usurp those functions the controller does best. In most instances where large aircraft and hundreds of lives are involved, the pilot's judgment, experience, and other qualifications for performing these ATC functions are better than the average qualifications of the controller. What is most significant is that the pilot is where the action is--he has directly at his fingertips the controls for track, spacing, velocity, descent, climb, turn, etc. Furthermore, he knows what can and cannot be done within the confines of flight dynamics, turn radius, acceleration, deceleration, etc. Controllers only know such flight parameters in general, and must observe, detect, and transmit corrections to the pilot--a time consuming and partially "open-loop" process since variable and long time delays prevent good ATC-rate information. A pilot can observe continuously ATC track speed just as he observes air speed and provide fine adjustments, whereas a controller has no such data and uses crude, randomly timed changes in gross velocity. ATC must be designed as a massive, complex servo

system with dozens of loops, each with adequate rate data to prevent "hunting" in servo language or "overload," "delays," or "stacking" in ATC language.

B. MECHANIZING PILOT PARTICIPATION IN ATC

Mechanizing pilot participation in ATC will probably become one of the most controversial ATC subjects of the 70's, because there are so many potential means for giving the pilot the displays he needs in ATC. His position, track, track speed, track deviation, spacing to aircraft behind, spacing to aircraft ahead, above and below his changing position, all typify the data involved. The amount, quality, and utility of this ATC pilot data will vary according to traffic density, locale, and type of aircraft, ranging from a Cessna 150 "shooting" a "400 - 1 mile" approach at a remote field to a 747 "shooting" a CAT III (zero visibility landing) in dense New York traffic.

One of the simplest concepts is to relay the "picture" that the ground controller already has, using a TV system for remoting the picture, to the pilot. This technique has drawbacks and disadvantages as noted by many and summarized in an MIT report (reference 4). MIT suggests that a data link with coded and processed SSR information be used. An airborne computer-processor selects the desired information from undesired SSR information for the pilot's display. Such a display is a cathode-ray tube in the cockpit with the pilot's "own" position in the center and "others" positions about him. Synthetic targets created by the computer are used rather than the usual poorly defined "blips" associated with typical radar displays.

In the FAA-DOT ATCAC report (reference 17), another concept known as IPC (Intermittent Positive Control) was conceived by the "Alexander-Goldmuntz" committee. In IPC, an up-link Discrete Address Beacon (DABS) is used to transmit data to aircraft much like the current national down-link of 4096 codes, which is used in the SSR transponder system. The up-link is a sophisticated data-link channel with a sophisticated decoder and processor for the pulse codes required in the air. In such designs the decoding,

processing, and display of data is often much more complex than the initial "encoding" means. On the ground such a decoder processor is of little concern and is usually serving many encoders. In this proposal, however, the complexity is in the air--a serious drawback. This IPC up-link will give "commands" addressed to the specific pilot such as "up," "down," "right turn," "left turn," speed changes, etc., effectively replacing the voice commands now used in ATC. In IPC, the pilot would not have an on-board plan position display of the positions of other aircraft. A message display of the annunciator type provides selectively addressed pilot-oriented and filtered "commands" (of the ground control sensed data that the ground computer generates).

Other competitive concepts prevail (reference 37), such as in the ATA-CAS (Air Transport Association, Collision Avoidance System). In the ATA/CAS concept the air-to-air sensing of other aircraft can conceivably measure the air-to-air separation (range) between two aircraft and their position relative to ground stations using multilateration (pulse and CW Doppler) techniques.

Another candidate to be discussed in depth is the use of a nationally broadcast, precision grid system of uniform granularity. This system would be useful (1) at all altitudes and (2) to all users for creating the on-board position of the specific aircraft. By using simple timing signals this grid can be related from one aircraft to another aircraft. Both air and ground have equal accuracy.

By comparing in the aircraft and on the ground the aircraft's position relative to the desired ATC position, both pilot and controller are now equals in the ATC process. If desired, all aircraft of concern and the ground central ATC system can determine by reception of simple timing marks (not a data link) whether the desired spacing, speed, and track deviation of the aircraft is occurring. All data is in simple synchronous time markings as a part of and in terms of the signal format of these superior coordinates (reference 11).

This national grid system of high-quality coordinates is aimed primarily at the missing half of the ATC control loop--the

pilot and the controls of all types of aircraft (airlines, military and particularly the (projected) 200,000 or so general aviation aircraft). Cost and performance must be adequate for all levels of users, even "Cessna" 150 users.

C. OPTIONS FOR MORE PILOT PARTICIPATION IN ATC FUNCTIONS

We must identify several practical options for this new national service consisting of (1) a uniform position-guidance grid and (2) SSR surveillance, so that adequate validation testing can be completed. A designated government authority can then adjudicate the matter on the basis of quantified, measured and tested (1) technical merits, (2) economics, (3) funding levels, (4) savings, and (5) cost benefits to the users of <u>all types of aircraft</u>, all types of airspace, and all densities of traffic.

Until these options have had perhaps 10 to 20 million dollars spent in many objectively oriented R & D programs (averaging about 100 thousand dollars each), there can be no such objective determinations. We are relegated otherwise to only the committee reports and committee designs we are all so familiar with, and which usually contradict each other.

We can develop a matrix of many typical low-cost validation efforts that should be a combined nationally oriented effort of DOT/NASA/DOD to create a total national plan. We now have a model of how to create a new national plan. The many microwave landing developments of the years 1961-1968 permitted a 1968-1971 (RTCA) analysis of what a plan for a new national system (costing about one billion dollars) would look like technically and operationally. It is suggested that we follow this same political-technical-operational route here but only after the several $100,000 projects are completed, thus providing adequate sources of measured, "real world" data on which to base the decision-planner process. Current technical data is completely inadequate for such a plan in spite of the many well-intentioned committee reports on future ATC concepts.

Certainly, one of possibly three future ATC options should be the concept herein called Broadcast Control of air

traffic. The main objective of this concept is to involve the pilot in the ATC loop to a much greater degree in the future. In so doing, we can add to the ATC system more integrity, reduce the controller workloads, prevent "over-dependence" on automation (computer control) of ATC, and, most importantly, meet the cost-benefits criteria of all users. Primarily, users down to the lowest economic strata must be accommodated so that they are in no way excluded from the ATC system. They are now probably being discriminated gainst with plans for costly three-dimensional VORTAC Area-Nav, IPC, CAS, data links, etc.--proposals that could readily run the minimum electronics cost to enter any ATC area (called positive-control areas) to about $50,000.

"You get what you pay for" in aviation as elsewhere, but the minimum service for the lowest economic strata of aviation should be in the "less than $5,000" category for ATC (transponder), PWI, communications (voice-VHF), guidance-navigation (VLF-LF) displays, etc. Assuming that all electronic elements for basic ATC are as widespread in production (and thus cost reduction) as are the current ATC transponders that sell now for $500, yet meet FAA/RTCA/ICAO specifications. In about $600 steps we would have a "minimum operating characteristic" (MOC) so that each function would cost between $400 and $1,000, giving a total of about six to eight major functions for full ATC within a $5,000 limit.

III. THE DESIGN OF AN ATC SYSTEM FOR PILOT USAGE

Since this discussion is oriented toward design of ATC for the pilot rather than the controller, a short historic analogy might clarify this philosophy. The critical aspects of the pilot in any new aeronautical venture are best dramatized by the unintentional competition between the Smithsonian Institute and the Wright Brothers--the goal of each being the first to discover a practical man-carrying, powered aircraft. The Wright Brothers were both the designers and the pilots of the research aircraft. They appreciated the non-mathematical aspects of the human pilot requirements to such an extent as to spend two years in preparation for their powered flight by building gliders, teaching themselves to fly them in a safe environment (over sand dunes), and, most importantly, means for the pilot to control the powered aircraft (elevators, rudders, and wing warping). Although powered models had flown before in calm air with pitch and yaw controls, apparently only the Wright Brothers appreciated the full significance of roll control as being essential to the pilot. This they gained from studying the piloting problems first-hand, inventing roll controls about 1899 and building them into gliders for pilot tests preceding the design of a powered man-carrying aircraft in 1903.

The Smithsonian program to develop the first aircraft was on a grander scale and resulted in an aircraft, engine, and pilot to be launched from a ramp built on a large houseboat, anchored in the Potomac River. The pilot was simply expected to ride along the elevated catapult track and after acceleration fly out over the water, having never piloted such a device in the air before. This seems to imply the Smithsonian scientist believed that piloting was a minimal matter, perhaps as simple as riding a bicycle. Of course, aviation history notes the immediate crash of the aircraft in the river. Years later it was argued that the Smithsonian aircraft could have been successfully flown in all environments, but this proved false in an actual analysis, as roll control was not part of the design.

However, the main point to be emphasized is that the very invention of the airplane itself was only possible by the direct involvement of the pilot in the process. The Wright Brothers succeeded where others failed, since they were the pilots and comprehended the piloting problems as well as the aeronautical problems. Although ATC engineers cannot always combine both disciplines of pilot-engineer, it behooves the ATC engineer to fully comprehend the pilot-aircraft aspects first before proposing changes to our aging ATC system.

Today pilots and engineers know how to control aircraft, to keep them aloft, and to land them. However, the new era of aircraft control in the 70's and 80's is one of precision, three-dimensional control in a defined airspace environment along with many other aircraft and in nearly zero visibility.

To avoid collisions with others, the safe, efficient passage through airspace filled with unseen aircraft and to land without seeing the runway is something that again demands the <u>full involvement of the pilot</u> before it is solved. The electronic specialist who, like some early aircraft inventors, ignores the pilot and does not study and fully understand how to include him as an integral part of the design of new ATC systems, will meet the same fate as those who did not appreciate the pilot involvement as the Wright Brothers did. The Wright Brothers were proficient designers of wind tunnels, engines, propellers, control surfaces, structures, and total systems, but every aspect of the design considered the pilot as the control element, and each aspect of the system design was tailored to his needs and survival; so it should be with the design of ATC for pilots.

From the foregoing views of future ATC systems, it is important to analyze each step of the many competing concepts. It will be argued that the Broadcast Control concepts not only should be realized for less costs to all users as well as to the government, but that added integrity will make the system safer, will have greater capacity, and will involve the pilot in an optimized manner. The rationale for such views is complex and will be presented in variations to attempt to clearly state this major issue

that will determine the success or failure of our ATC modernization efforts in the coming decade. Clearly, when we enter the domain of the pilot, his psychology, abilities, and limitations, aircraft pilot displays, pilot responses, aircraft responses, etc., in Broadcast Control, we are depending upon a clear understanding of all of these functions separately and in combinations under an ATC environment. These considerations cannot be left only to electronic engineers, controllers, or installers of electronics. Such pilot-ATC responsibilities must be determined by engineers with inter-disciplinary training and experience in aeronautics, flight dynamics, pilot psychology, pilot response, and the coupling of the pilot and aircraft into a cohesive unit when reacting in a given ATC environment. Neither can we leave this problem to a mathematician who writes a formula for the pilot control loops and leaves it there. We must now learn to provide the full communications essential between the aeronautical and electronic aspects of ATC.

A. SOME SPECIFIC PILOT-ORIENTED ASPECTS OF ATC

Probably most important in ATC planning is to establish what the pilot participation should be in ATC. The first step is to make a list of the future ATC areas he will potentially participate in, making sure the list is comprehensive. Then we will examine means to validate his participation in each area and compare it to the ground control portion to assure that the pilot and controller complement each other and are interfaced optimally. Then we can trade off the ground-oriented ATC functions against the pilot-oriented ATC functions, creating what redundancy is needed from a total system viewpoint. We then create a more balanced concept of ATC and future trends than now exists. What is currently lacking is this understanding of the pilot and the tools to do his job. At present we are heading toward more and more ground domination either in the control process or in over-burdening the ground electronics or controller. The added traffic loads of the 70's will overload such ground control concepts beyond what can be done safely and is economically justified. Enormous new capacity is needed in ATC for the ten times growth indicated for 1990 (references 6 and 7).

To cite a specific example illuminating the last point, let us note how the SSR L-band radar-ATC surveillance system operates for data to the ground controller and how it compares with the pilot data. According to FAA reports, this system used as a measurement tool is accurate to less than 0.1 degree in angle (out of 360 degrees) and has less than 200 feet of error in range (out of 200 NM).

This does not imply that all SSR data supplied to the ground controller is this accurate, but even if degraded, we would have a 0.2-degree and 300-foot granularity in the surveillance system. At 60 miles from the SSR, 0.2 degree represents about 1/300, or about $\pm$1/5 NM. Compare this with the pilot's VORTAC data. The end product of aircraft position via VORTAC R-Nav is about $\pm$4.5 degrees for 2 sigma (95-percent probability) or $\pm$4½ NM at 60 miles. It is clear that this is about a 20 times degradation of pilot data over controller data. VORTAC ATC errors include the VORTAC ground station, airborne receiver, and piloting display errors. Although the electrical errors of VORTAC total only about $\pm$3 degrees, the inability of the pilot to use the VORTAC information any more accurately is determined to be about $\pm$2.5 degrees according to ICAO and FAA reports, which clearly state this limitation and illuminate the large discrepancy of 20 to 1 between controller ATC inputs and pilot ATC inputs.

The interrelationships between what is called "Flight Technical Errors" and the (electrical) station, VHF propagation, and receiver errors is very direct. A pilot cannot be expected to fly a course (whose indication of center is in error, "wanders," and has "bends") to anywhere near the accuracy that he can fly a course that has minimal errors, bends, or perturbations using a stable display of optimum sensitivity.

Thus, a system with poor display accuracy and course perturbations (not resulting from aircraft displacement) causes the pilot to amplify the total track deviation and thus add ATC errors. The final aircraft position and guidance efficiency (of VOR-DME created flight path perturbations that are caused by this 20 to 1 deficiency of pilot data) are finally viewed by the

controller using his SSR ground displays. Such track errors are greater than the electrical errors of the system. Thus, aircraft must be separated by greater distances for this reason, lowering ATC system capacity.

On the other hand, an ATC guidance-track-navigation system that does not create these piloting problems can be flown with far less electrical error which, in turn, means far less "flight technical errors." These improvements are interdependent, adding to the total useful system accuracy and thus ATC capacity-safety. The piloting aspect of "flight technical error" noted in our standard is very complex and seldom measured scientifically. We will outline some of the interrelationships that require analysis from the views of (1) the pilot and his displays, (2) the pilot and his "coupling" to the aircraft, and (3) the direct automatic coupling of the aircraft to the guidance system. All three of these generalized cockpit problems have their own peculiarities and must be fully understood before any of the many "future ATC" systems now being proposed for improved pilot participation in ATC will ever become a reality. Although dozens of reports exist on electrical errors of VORTAC, only one or two have been published on the impact of these errors on the pilot and the controller who sees the pilot as deficient through the superior "eyes" of the SSR in an angular system 20 times as precise as VORTAC.

B. SURVEILLANCE VS PILOT NAVIGATIONAL ACCURACY

Let us now compare the surveillance accuracy of ± 0.2 degree and 300 feet to the Area-Nav accuracy of 4.5 degrees and about 2,000 feet. Angle data is the critical comparison since the VORTAC angle is proportionately much worse than the DME range accuracy. This comparison is fair, since both are polar coordinate systems. Range error is usually a linear function not differing too much with increased distance from the emitter. Obviously, in a polar coordinate system, the angle errors, measured in linear terms such as miles, increase with distance from the source. The angular errors also vary in geometric orientation relative to the flight track direction.

The SSR error of ± 0.2 degree is displayed to the ground controller as a positional error of 60/300 or only 0.2 NM at a range of 60 NM, whereas the pilot's VOR total flight track error is ± 4.5 degrees, or 60/13, or about ± 4.5 NM. This difference of about 4.5/0.2 or in excess of twenty times is of major concern in any ATC system planning for the future where the pilot will be asked to become a more active element in the ATC process and must be able to do a better job than is now possible with VORTAC. In fact, identical accuracies of pilot-displayed position-track and controller-displayed position-track seem essential before any real progress can be made.

It plainly is not fair to the pilot and the aircraft control systems to compare the performance of an SSR ground display that is twenty times more precise than the basic information given to and executed by the pilot. Merely relaying the precise ground-derived data to the pilot (after computing, processing, etc.) is also unfair to the assessment of pilot ATC participation, since the pilot is then at the mercy of the same system as the controller, and any failures wipe out both parties and safety levels are decreased. Furthermore, SSR was not developed for pilots; only controllers were considered and all system decisions optimize the controller aspects of SSR, making its ground data basically a poor second choice for aircraft pilot usage via data link or any other means.

Thus, though one praises SSR for its ground-derived data, it is already working at full capacity and should not be further modified for both pilot and controller but should only be modernized to work better as a surveillance "only" system. No attempt should be made to make it into a navigational system by remote control means. It is dangerous planning and quite unfair to the pilot to assume that he will not be given directly a new coordinate system but only secondhand SSR ground-derived data. There are many shortcomings a massive electronic ATC system on the ground can cope with or a controller can modify by switching computers, codes, displays, radar inputs, etc., that the <u>pilot cannot do</u>, because all these controls are on the ground. To give to the

pilot the degree of sophistication that the controller has with his many inputs, multiple-redundant displays, computer back-ups, etc., would be prohibitive. This controller option is essential to safety in a central ATC surveillance concept as anyone can witness by touring an ATC center, such as New York, and then going through the basement areas viewing some 40 million dollars worth of electronic facilities and large technical staffs that create the "pictures" for the controllers' benefit.

Such enormous redundancy and complexity can be justified in a large building with 100 to 200 employees on duty at all times, since an ATC center serves up to 200 or more aircraft representing perhaps 10,000 lives at a time. A modern, high-density tower is somewhat less complex but still a major electronics marvel. Since an aircraft display of SSR remoted data would have none of this back-up capability, the pilot would be at the end of a long line of complex electronics with so many intervening elements that any one of them and particularly an added one (data-link) could create chaos.

There seems to be little the pilot can do to become a more active participant in ATC, as many ATC experts now seem to be suggesting, without giving him a new system that is equally suited to his peculiar needs and ATC responsibilities of track, schedules, and separation. Yet, any new facility for the pilot must be fully harmonious with the remainder of the ATC system. By going to the appropriate rectilinear coordinates of a wide based LF/VLF navigational system, we can give the pilot at low airborne costs a means (using a new national network of four to six stations), an excellent track system. On the average, the quality, accuracy, and coverage are equal to or better than those of the SSR system.

Although the SSR surveillance accuracy varies with range (being useful to 200 miles), we must recognize that ± 0.2 degree is a spread of error of about a mile, whereas in the parallel oblique coordinates of a specifically designed LF/VLF system for ATC in the United States the errors should be about 1,000 to 2,000 feet. Obviously, engineering precautions are used in the design of such an LF/VLF system using such features as automatic

diurnal corrections, higher station sampling rates, localized differential data, etc.

Each of these elements of a new ATC LF/VLF system does not increase the complexity of local usage of LF/VLF (or even Omega as it is), since the number of pilot adjustments, selections, etc., will be equal to or less than the number of pilot actions required for a VORTAC station to cover the same volume of airspace (say, 150 X 150 NM from the surface to 40,000 feet). Thus, in comparing the actual "real world" usage of the surveillance (ground) ATC functions of displays, computers, etc., with the airborne on-board derived data from LF/VLF coordinates, we will find on the average that the pilot LF/VLF data will equal or exceed in many cases the SSR data because of the limit of, say, 1,000 SSR stations in the United States. Meeting surveillance accuracy on its own grounds of total area accuracy means that a national granularity average equality is possible with LF/VLF systems. A 20 to 1 degradation (as in VORTAC) is also avoided as well as its similar line of site limitations. In fact, LF/VLF will be shown to provide many services to thousands of remote fields that would otherwise not receive any service from ATC.

This VLF/LF capability can be realized for as little an investment as $2,000 or less for airborne units designed for general aviation, yet suited for selection of way-points from a few miles apart up to hundreds of miles apart, with linear track deviation displayed to the pilot, as noted in a recent flight demonstration by a manufacturer. More sophisticated receivers, "course and way-point" selectors, displays, etc., could cost in an airline version perhaps as much as $10,000. In both the quality levels, the airborne units should still be lower in cost than comparable wide Area-Nav services using way-points, etc., from other sources, such as VORTAC, Doppler, inertial, etc.

IV. NATIONAL PLANNING FOR NEW ATC CAPACITY FOR ALL USERS

What is lacking in planning for a future national ATC system is something that obviously must be evolutionary in nature, but evolves toward more pilot participation. What is now needed is a series of tests and analytical treatments of the various candidate ideas. They are in the general classes of:

1. DOT/ATCAC; IPC "up-link" on the SSR transponder.
2. Telemetering and processing of SSR digital data from the ground controller's display inputs giving a cockpit pilot's display (using a cathode-ray tube).
3. Area-Nav using VORTAC with three-dimensional corrections and with its constraints of degrading angular errors.
4. Wide Area-Nav using techniques of LF/VLF in a national system derived from Omega. This will create a nearly rectilinear national grid whose average and uniform accuracy is 20 times better than that of VORTAC (in the worst cases) and about 5 times better in the average cases. With simplified time-sharing signals, the coordinates can be used in a roll call fashion for a low-density, low-cost surveillance, separation system as well.
5. Air-derived collision avoidance systems.

Each of these cases need not be examined too much in their electronic aspects except for No. 4, where not much data exists on aviation applications. Considerable data exists on the others.

What is needed is a means to evaluate the proposed methods for increased pilot participation in the ATC process--that is, what the pilot can do with the new information, whether it increases his work load, whether it works in both low and high density traffic, at major hubs and remote strips, and certainly whether the redundancy and integrity are increased, leading to greater safety. The so-called "flight-technical" aspects of the five solutions to pilot participation in ATC must be stressed in

evaluations much more than in the past. We will discuss some of the possible means of introducing in the engineering of a system the flight technical aspects, not just some pilot opinion poll as has often been done in the past. The total national planning for advances in ATC technology must assume that both the pilot and his aeronautic counterparts are as well represented in the decision process as the electronic experts and ground controller authorities. The latter now seem to dominate the national ATC decision processes.

A. THE MEANING OF "FLIGHT-TECHNICAL" ASPECTS OF ATC

The phrase "flight-technical" originated with the early post-war IATA and ICAO technical committees that were purposely balanced, giving the pilots and aeronautic engineers the "flight-technical" problems and the electronic engineers and the controllers the "radio or electronic" technical committee assignments. As noted previously, one of the best ways to introduce this subject is to cite a specific example.

In a system such as VOR, which has a total of ± 4.5 degrees of error, of which the rms value is composed of 3 or 4 sources--one being the pilot response to his VOR display at a value of about 2.5 degrees--it is often thought that this pilot or flight technical error component can be reduced relative to the other values. This is usually not true since the noise perturbations, multipath degradation, course bends, etc., often determine how high the flight track deviation indicator sensitivity can be set. This is a figure often empirically arrived at, based on estimates of pilots and with few scientific measurements. For example, if the flight track is a line in space, represented by a wavy, curved line due to multipath, low space pattern sensitivity, etc., the pilot will attempt to follow some of these undesired perturbations to the indicated VORTAC track, be it "raw" VOR or computed Area-Nav. The pilot in following a centered track indication, such as a zero-centered meter, must blindly assume that a given deviation indication represents a certain track error in space measurable in a given number of feet. He then turns his aircraft in response to the displayed deviation with his horizontal course indicator or other steering device that mixes heading and track.

Such combinations of track and heading are required to intercept the track and drop on it "dead-beat" without passing through it and then bracketing it to lesser amounts, requiring two or three damped cycles of track oscillation as recorded on the usual chart recorders.

If a rapid wind shear or other atmospheric turbulence occurs, this can shift the aircraft off course, resulting in pilot action (or autopilot action) to return to the center of the course. Even a perfect electronic path in space will still see these pilot maneuvers in rough air causing the aircraft to conform to its earth-referenced course and track in space. These changes can often be small, if accomplished without delay, requiring small deviations (corrections).

For example, in an ILS approach, the full-scale pilot indication at threshold is ±150 microamperes for ±350 feet, shown in a display about ±2 inches in dimension. The pilot is expected to control to a threshold condition with a flight technical error of no more than about 20 feet, according to the tentative ICAO and FAA guidelines on CAT II and III operations. This means that the pilot-displayed error must not exceed about ¼ inch. However, if this sensitivity (±350 feet) were used in an Area-Nav display, based on VOR inputs, the indication would be so unstable as to not be usable. Usually sensitivities of about ±2 NM (±12,000 feet rather than ±350 feet) for full-scale indication are used. With an indicated course width of 4 NM or about 24,000 feet vs the 700 feet at the runway threshold for ILS, pilots must be adaptable, but the spatial guidance stability in feet must be high in the latter case.

ILS simply has much more antenna sensitivity (or space pattern change) in db per degree and is at a closer range so that this difference of about 25 times in the pilot deviation indication is necessary to provide stability in VOR displays. Thus, the pilot must fly with widely varying "gains" in his responses to these indications. Certainly a 50-degree heading change on a VORTAC at 50 NM will create a slowly changing deviation to correct an error back to center. However, if this 50-degree intercept angle

were used in an ILS approach near the airport to correct a ¼ scale deviation, the pilot would overshoot the course and go into a maximum deviation in the other direction in a few seconds. Pilots are apparently extremely adaptable to this type of display variation and do the best jobs they can. However, as noted, we are now giving the pilot only the ability to position his aircraft less accurately by a source of data that is as much as 20 times worse than the ground controller's data. If we now say to ourselves, "how do we have the pilot fly a track in space so that he will be within much smaller error limits as the controller's display indicates than we have in the past," we will see that the quality of guidance must be higher, approaching ILS quality rather than VOR quality. If this pilot response occurs, many things accrue automatically to the benefit of an ATC system, the controller, and the pilot.

First, the communications load is reduced, since pilot errors are reduced and he is where ATC desires him to be rather than up to a few miles off course. Secondly, we can ask the pilot to adhere more closely to his spatial track, thus increasing the separation between adjacent tracks. Third, since the LF/VLF track is created by a rectilinear type grid system--equally accurate longitudinally as well as transversely to the track--we will now ask the pilot to observe track speed and separation in dense traffic, greatly smoothing traffic flow. This track velocity is equivalent to the ground speed indication often used with DME when it is known that the track is on an absolute radial to the station. Such a case is a DME on the localizer course, where the aircraft is always on a radial-only path. In Area-VORTAC-Nav, this track speed is not available, since the VOR rate is 20 times worse than DME, and the geometrics of the R-Nav track will encounter these large track speed errors. This lack of suitable track-rate information from Area-Nav VORTAC is a serious ATC limitation.

In LF/VLF techniques this ground speed feature, admired by many pilots but only available in a very limited way in VORTAC, is at least theoretically available on all tracks in all directions, with uniform track velocity outputs. Admittedly, the U.S.-only

LF/VLF complex must update about once every 3 seconds. This essential pilot ATC function cannot be realized with any useful accuracy with VORTAC inputs, since the angular perturbations, station to station registry, height corrections, slant range errors, etc., all create a track velocity that is also unpredictable and up to 10 to 25 times worse than the ATC track velocity as computed in the ground computers for the projection of conflicts and avoidance of collisions. The present position of the aircraft is extended electronically for a given time into the future as are all other aircraft to detect obvious conflicts or potential collisions and informing the controller so that he can anticipate before the occurrence as to what is the best maneuver to avoid the case.

Thus, we can envision that the pilot with the uniform navigational grid system can observe a cockpit display, much like an airspeed display, using standard cockpit instrumentation (not "pictures" or cathode ray tubes), to obtain the actual track speed. If all aircraft have an assigned track speed as well as three-dimensional tracks in space that are coordinated initially in a flight plan integration (via a flight planning computer program), then we have a system that can run with little controller intervention. The pilot has more incentive to adhere to such a plan than even the controller, since his immediate safety and expeditious operation are at stake.

For example, it would be quite possible to test pilots under synthetic conditions, using the two methods of maintaining spacing between aircraft (air-derived and SSR-telemetered from the ground computer). At the same time the displays must assume that the track speed is correct (in addition to spacing fore and aft with respect to other common track aircraft at the same altitude). When the aircraft is alone without immediate spacing needs, the track speed may be just as significant since an airway juncture is ahead, forcing the single aircraft into a track containing a stream of aircraft. The aircraft's spatial "slot" of time and moving position must be accurately filled by achieving both track speed and positional accuracy in three dimensions on the path prior to the intersection with the other traffic.

It is believed that the pilot will prefer a standard instrument indication for this with a "bug" that is set by the pilot or by ATC communications to the desired track speed, just as an airspeed "bug" is now set. Such features are difficult to add to a cathode-ray display that is a relay of the ground controller's ATC displays with selected data. The intent here is not to modify the principles of pilot displays but to suggest what new pilot displays are needed for ATC reasons. These new displays should be consistent with what the pilot now accepts, which is 90 percent electromechanical displays rather than cathode-ray displays. One reason the relaying of ground sensed data is probably a poor technique is that to obtain track velocity the SSR system would have to repeatedly compute it for each aircraft and transmit the separately addressed data continuously to every aircraft--an enormous burden for ground computers, data link transmission systems, airborne data link receivers, processors, and annunciator displays. A major part of the complexity of track speed measurement is avoided by direct on-board measurement of the traversal of the grid coordinates in space, using a rectilinear type, national grid. All aircraft would use the common earth-referenced grid in a given airspace, thus both rate and displacement data would be fully coordinated between all users; something not possible with self-contained systems such as Doppler or inertial navigators.

B. INTRODUCTION OF RATE FEEDBACK INTO ATC

Any modern servo system uses two basic signals: one is displacement, and the other is rate (of change of displacement). The rate is often measured in mechanical servos with a separate rate type generator in addition to the usual displacement synchro-repeater that provides only displacement. Without rate in a servo system we have oscillations. If the oscillations are reduced by lowering the displacement sensitivity then we have delays, errors, etc., because of the sticking of the gears, etc. Consequently, neither solution is adequate with displacement-only systems, and some 30 to 40 years ago "rate" was added to mechanical servos (particularly in central fire-control systems for Navy ships).

However, in aviation ATC systems we are still working with an old-fashioned displacement system as far as the pilot is concerned. He essentially gets only the crudest of rate information such as arbitrarily assigned airspeed limits in terminal areas. These corrections are in large steps, with long periods between sensing and results (feedback is poor). They are of little value when spacings of, say, 3 miles or less are desired on a common ATC track. In visual "station-keeping," where the ATC tells the pilot to "follow the aircraft ahead," the pilot, by visually judging the distance to the other aircraft using its image size, direction, etc., is able to maintain remarkably accurate spacings. The controllers also assist with radar vectoring where instant-by-instant changes are commanded by voice.

However, as the ATC system becomes more loaded we must provide this "rate function" in some other way as the need for it will increase astronomically with the traffic density and closer spacings, making these current practices inadequate. Since the pilot has at his fingertips the actual rate controls in three dimensions--the throttles, drag elements, pitch, roll, etc.--he should be given an instrument with a direct display of his track velocity and then be permitted to adjust the aircraft according to its own peculiar needs that only he is aware of, such as weight, peculiar flight dynamics, and any unique problems, such as partial power. He does this so as to continuously maintain this track speed to within perhaps 2 to 3 knots rather than wide limits of 10 to 20 knots (possibly the best now available). Often a common terminal area track speed for all aircraft is used, and this assists greatly as one of the worst problems in ATC is variation in track speed of different aircraft in a mixed air traffic pattern. However, this implies variable airspeeds depending upon direction of flight, wind direction, wind velocity, wind shears, altitude, etc.

C. NON-PRECISION APPROACHES TO THOUSANDS OF SMALL FIELDS

Any future ATC plans should also accommodate the tens of thousands of airspace users that operate in the opposite environments to those above, namely, in low-density areas. Avoiding collision with high obstructions and providing a universal let-down

procedure would solve the major problems. As we will see, LF/VLF coordinates are ideally suited for these applications, and with VHF communications and a transponder, a very-low-cost Area-Nav approach system is possible.

In addition to meeting some of the dense ATC environmental problems, it is essential that the pilot participation also be involved in those geographical areas where medium- and low-density air traffic exists. Here, the mid-air collision is not such a risk as collision with the ground as noted in an ICAO survey. Collisions with the ground are the most prevalent fatal accident in aviation--be it landing, approach, enroute, blundering into mountains, altimeter errors, etc. The solution to this low-density problem is as much a part of our national ATC system as solutions to dense traffic problems.

It could be that we can solve the ATC problem of a few high-density areas with an abundance of everything, raising the participation costs and driving much aviation into the country and remote areas where essentially no facilities exist. This would create added traffic that would be exposed to higher risks because of lack of facilities to avoid collisions with the ground (and with others), since no adequate means exist to provide coverage of the thousands of possible areas for small airports.

The IPC concepts would not work in such environments as the enormous amount of ground equipment and computation would not exist for it. The cost of the airborne receiver, decoding, etc., is beyond the reach of general aviation. This does not infer, however, that the basic SSR system will not spread its coverage throughout the nation to perhaps a 1,000-station network of the contiguous 48 states, since a basic station may now cost markedly less with modern digital designs (about 400 such simplified SSR ground stations are being purchased by DOT/DOD).

Thus, we will have surveillance functions covering the nation, using the estimated 100,000 transponders operating in aircraft in 1975. The sophisticated computers, displays, etc., will be only at major centers and airports that "net" many radars and other devices. The high cost of an IPC site, such as a complex

cylindrical phased array (see ATCAC report, reference 7), will cost many times more than the simple stations using a small rotating SSR antenna. Thus, "Basic-SSR" will be quite prevalent in low-density areas, but not IPC or DABS. It is argued here that the LF/VLF grid will cover all areas with equally good coverage whether they are low-density or high-density traffic areas, and thus we should base the use of the future ATC system on elements that meet both criteria.

A typical example is a so-called VOR "Let-Down" procedure which is widely used in low-density areas and has contributed to many recent airline and general aviation accidents. This is a procedure where a pilot selects a VOR radial that may or may not emanate from a VOR on or near the desired airport. It may be a radial to a remotely located VOR, as most of them are. The pilot then starts down the VOR radial from some navigation fix crossing the radial, perhaps another VOR radial or a marker. This initial point of descent on a non-precision approach is such that the pilot is from 5 to 10 miles away from the threshold of the runway at a given altitude and descending at a given sink rate. The pilots have charts giving the sink rate for each VOR let-down. Sink rate is measured by rate of change of air pressure and has many limitations as does the barometric altimeter, both being pressure gauges of slightly different design but not inherently related in any manner to the physical height above the runway elevation.

These approaches are often to such limits as "400 and a mile," meaning that the pilot descends without seeing the surface until he is at a 400-foot elevation above the airport and has 1 mile of horizontal visibility at and below 400 feet. Both of these values are poorly determined at most small airports as ceiling and visibility measurement instruments are costly. A typical VOR let-down is shown in Figure 1. To understand the method now used for establishing these criteria, one must study in some detail the "TERPS" manual (Terminal Instrument Procedures) describing authorization of these non-precision let-downs. If a favorable case exists with a VOR actually on the airport, low ceiling visibility values may be assigned. The lower the limits can be established,

Not to scale

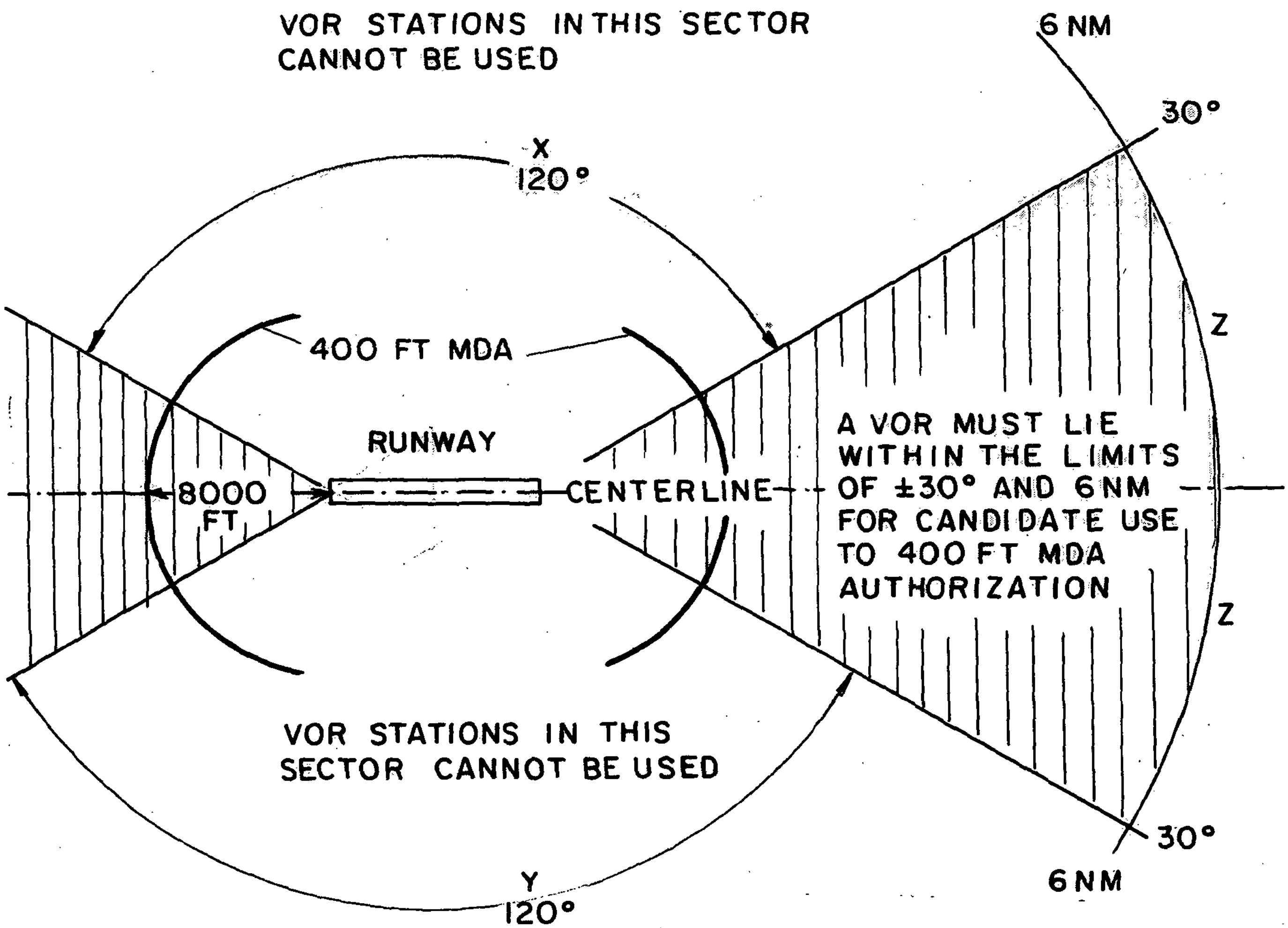

FIGURE 1 TERPS LIMITS ON USE OF VOR NON-PRECISION APPROACHES TO 400-FOOT MDA

obviously, the fewer the cancellations due to weather. Airport operations occurring on an annual basis are used for most economic analyses and make an airport with low limits a more commercially viable operation. Many small feeder airlines operate under such non-ILS conditions as do air taxi operators and third-tier carriers; yet all such users carry the public for hire.

If, however, the VOR is at some distance off the airport and is not aligned on the extended centerline of the runway, then a higher limit of ceiling and visibility are imposed, meaning the airport is shut down more frequently and the commercial aspects suffer. The major factors in determining the visibility limits that may range from a minimum of 300 feet to a 1,000-foot "ceiling" are described as a Minimum Decision Altitude (MDA)--a phrase meaning a glide path or ILS is not available--they are: (1) the off-airport distance to the VOR (or ADF fixing source), (2) the angle a radial from the VOR makes with the runway centerline (not to exceed 30 degrees), and (3) the local conditions of terrain profiles, barometric reference sources, etc.

For example, for every added mile beyone 6 NM, any VOR used for such an approach requires that the MDA value be increased by 50 feet per NM. Thus, if a 400-foot ceiling could be authorized for a close-by VOR, if the VOR were actually 10 miles away, the ceiling (MDA) would be about 600 feet. The best authorization might be 300/1 mile, and the poorest might be 1,000 feet and 2 NM. This is a very large range of weather minimums, and the exact values are selected by somewhat non-scientific standards. Many recent accidents indicate that changes in the criteria and the basic concept of using VOR for such high-risk operations are now in order.

There is obviously a major restrictive impact in many parts of the nation if the higher limits of MDA are used; on the other hand, great financial advantage and better service is available if the lower, non-precision limits are used. Of course, if one wants to go to ILS (glide slope, localizer, markers), lights, transmissometers, etc.--about a $500,000 investment beyond the typical VOR let-down (non-precision authorization)--then a 200 and ¾ mile or even a 200 and ½ mile precision approach criterion

might be authorized at good approach locations. The cost for lowered ceilings probably goes as some inverse power of the MDA height, being possibly one unit for a "1,000-foot and 2 NM" MDA limit, and ten times that for, say, a 350-foot MDA limit, then rising to perhaps 25 to 50 times that for a precision approach to a 200-foot Decision Height (DH is a phrase used with precision glide path, localizer, approach limits, markers, etc.).

It is obvious that with up to 10,000 or more small airports and fields in operation by 1990 the facilities cannot cost $500,000 for precision and approach capability. Furthermore, we cannot tolerate having the MDA limits so restrictively high as to make the airport facilities, hangars, runways, fuel, radio communications, real estate, low-cost lights, etc., a losing proposition. No one will operate these much needed, small airports.

D. CRITICAL COMPARISON OF VLF/LF APPROACHES TO VOR/ADF APPROACHES

An analysis of the TERPS manual indicates that one of the major decision points on MDA is the location of the VOR or ADF facility. Since VOR is far more likely to be used, we will continue the comments on this facility for analyzing the operating and safety benefits of LF/VLF approaches in place of the current non-precision approach procedures and systems. Probably the key criterion for MDA is that the VOR must be within 6 NM or less of the airport, or on the airport, to qualify for a low-visibility authorization, such as "400 and a mile." This specific value is picked as being somewhere in the middle of the dozens of MDA/DH authorizations ranging over 10 to 1 from 1,000 feet of altitude to 100 feet of height, and from a horizontal visibility (also ranging over 10 to 1) of 2 NM (12,000 feet) to only 1,200 feet for CAT II ILS.

If such an authorization as "400 and a mile" were available on a national basis nearly for "free" to all airports, regardless of size or location, this would be a major benefit to all airspace users, airlines, general aviation, VSTOL services, air taxi operations, private flying, business aircraft, etc. In fact, this ATC capability alone could set into being a chain reaction wherein the small aircraft no longer will be attracted to operate

and depend on the large airport facilities, such as VORTAC, SSR, primary radar, extensive lighting, DME, glide slopes, localizers, surface detection radars, etc. A nationally available (400 and a mile) authorization could create a suitable reason for attracting many aviation operations to more remote areas. Industrial parks are now very common, some states installing up to 50 such small airports, each as the heart of an industrial park, so that the 400 and a mile authorization would allow good reliability in most places and enhance the safety of all operations. If growth occurs, then ILS could be added, but most importantly the dispersion of aviation would take place, which is essential to the sound planning of any future ATC concepts as well as to the users of corporate and general aviation aircraft. Effectively, services with many options are offered with the cost benefits of a given aircraft usage being the determining factor.

If, however, we must have at least a VOR on each small airport to obtain this 400 and one mile authorization, we will not succeed, since the cost of the VOR is still about $50,000 when properly installed and monitored. Even if this cost and the continuous inspection and maintenance costs could be met, there are few new radio channels available for adding, say, 3,000 VOR stations to small airports (one in three out of the projected total 10,000 population by 1990). The 6 NMTERPS criteria eliminates nearly all cases of a single VOR serving two airports. This is particularly true when it is desirous to have the VOR on the extended runway centerline as noted by the FAA in AC-150/5300 (reference 17). We must, therefore seek another means of providing this major step in ATC technology.

As will be seen, it will be the use of the same concepts of LF/VLF sensors that permit the pilot to become more a part of the "ATC Loop," using on-board, low-cost equipment. Another serious VOR constraint worth mentioning is the fact that the VOR letdown must be along a line of position in space from or to the VOR that crosses the runway centerline at angles no greater than 30 degrees. This criterion again severely limits the VOR authorization of a low MDA at many airports. Thus, the 30-degree and 6-mile rules of TERPS would force at least another 2,000 to 3,000 VOR

stations on the air to give a broad national use of "400 and a mile" or possibly "300 - ¾" criterion (see Figure 1).

To re-emphasize the unsuitability of such a VOR expansion, it would require radio channels that do not exist, cost probably over 100 million dollars for installation and about 5 to 10 times that amount for the "life-cycle" cost of modernization, maintenance, adjustment, monitoring, flight inspection, etc. A total national cost for a life cycle of 15 years for a national 400 and one mile capability using VOR would be about a billion dollars. For VOR this would be added onto the current need to modernize the VORTAC network with "super VOR's" such as the Doppler VOR, increasing the total life cycle cost to perhaps 1.5 billion dollars. With knowledge and experience gained from 20 years of LF/VLF guidance and navigation development, testing, and operation of such systems as Loran-C and Omega, we could readily engineer and install for about 50 million dollars an entirely new network of five or six stations designed solely for the future ATC need to add Broadcast Control and to serve all economic levels. Life cycle costs would be much lower for technical reasons.

It is with such a view that major investments will be made. At least a few million dollars (20 or 30 of the $100,000 validation and test studies) should be expended on LF/VLF by DOT/NASA/DOD before any decision is made. With such validated information, good economic studies, operational tests, and a truly scientific source of validation, data exists from outside qualified sources to assure objectivity in the decision process. In other words, don't just extend VOR endlessly, since that is all the FAA has in inventory and the urgency requires it, but provide an early option that may be far superior.

If, say, a case can be made for another 1,000 VOR stations, we would then have a total national investment in 2,000 VOR stations, many with double costs if DME is added in the so-called VORTAC versions. This would become a major cost burden to the FAA budget. Aside from that, the new channelization scheme of 25-kHz VHF channel spacing would be mandatory in an attempt to find enough channels for 2,000 VOR's. This subsequent, forced change would shortly require the replacement of over 100,000 private

VOR/VHF receiving units with more expensive units, each costing at least $1,000 (so-called NAVCOM units). Without expanding VOR we would avoid this total additional cost and channelization chaos, leaving VOR as is for many years since it complements the LF/VLF equipment in use.

E. APPROACH GEOMETRICS

It can be seen from Figure 2 that a VOR must almost always be associated with every airport if there is any hope that a national usage of a 400 and one mile criterion meets all requirements of safety, etc. Many collisions with mountains could be eliminated since LF/VLF is two-dimensional and VOR is one-dimensional. We must remember that the pilot will be dead-reckoning in the vertical plane, using the error-prone barometric altimeter, because no checks along the VOR approach are available except the outer check point that may be in error by a mile (since it may be an intersection of two VOR radials). However, the pilot will usually not be heading along the direction of the runway when he obtains his first visual contact and this is such a wide area, ±30 degrees, that it could be very dangerous with VOR (Figure 3).

Furthermore, the vertical descent plane could be in error with an error in the outer check point and the next point, say, the descent from a typical 1500-foot altitude (above the airport starts). If a typical 3-degree slope is assumed (in the sink rate), dead reckoning then will occur along the descent path. This operation of estimated actual height is along a path 1500 X 20 or 30,000 feet long (or about 5 NM). Typically, head winds, wind shear, barometric error in setting or use, and the horizontal variables (up to 30 degrees off-axis) make VOR let-down a very unattractive future concept even though acceptable up until now.

Several accidents in the years 1969-1971, including some airline accidents in the Northeastern part of the United States, can be traced to poor VOR let-down procedures, wherein the total procedure has so few checks and balances that its use is hazardous, even for the highly trained airline pilot.

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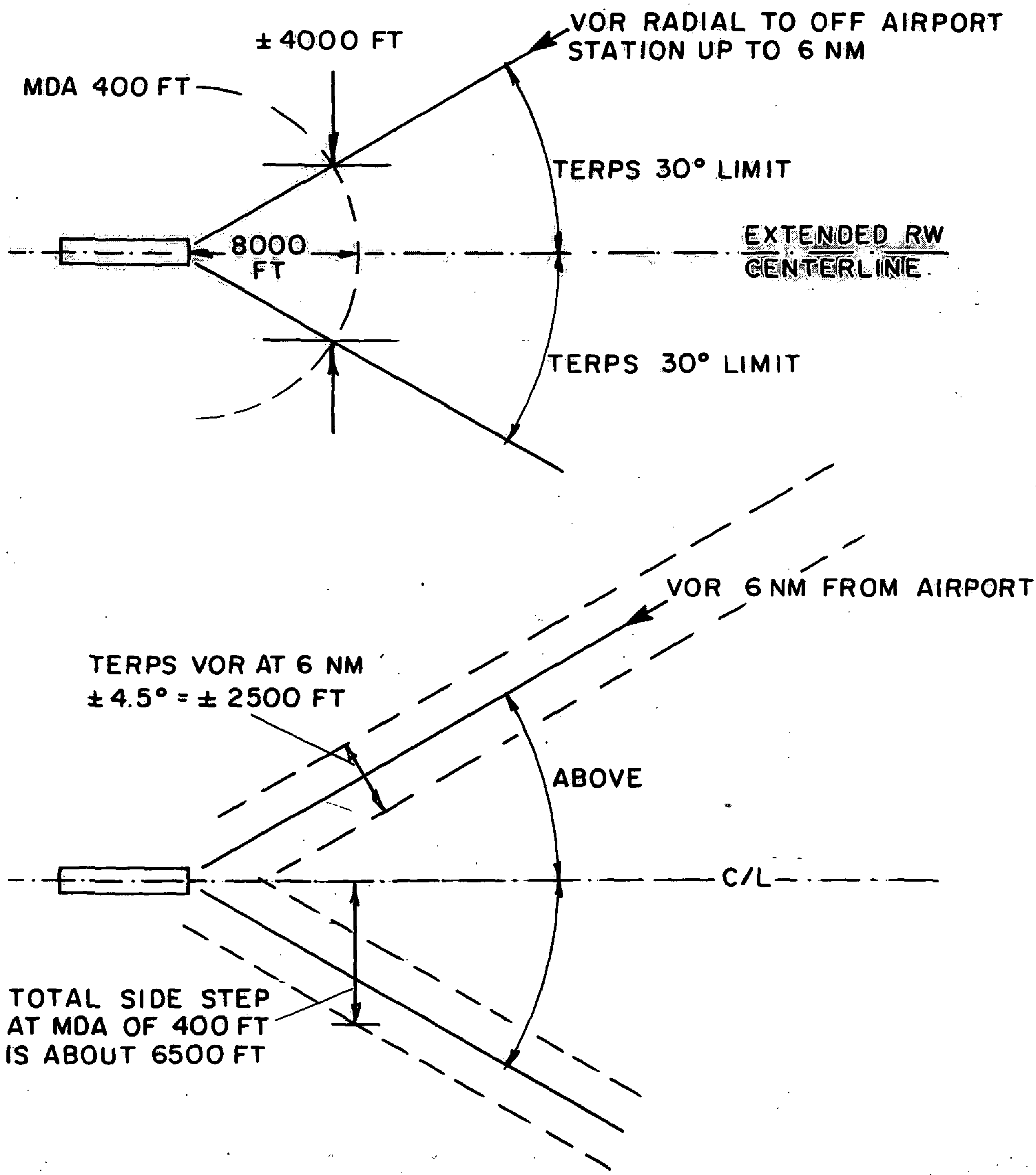

FIGURE 2 VOR TOLERANCES FOR TERPS NON-PRECISION APPROACH TO A 400 AND 1 MILE MDA

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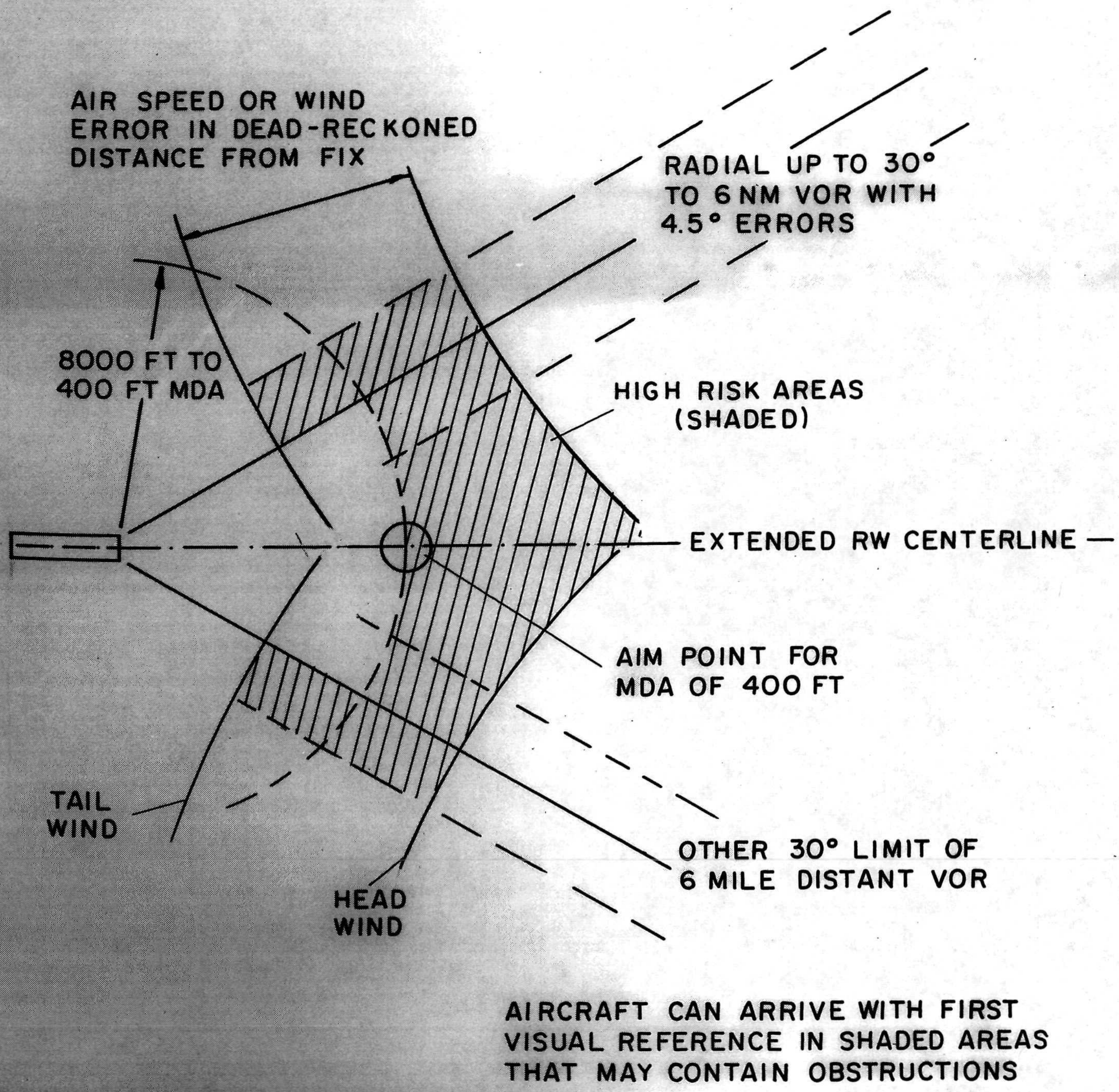

FIGURE 3 SOME OUTER LIMITS OF VOR LET-DOWN ERRORS AT AN MDA OF 400 FEET

F. VLF/LF LETDOWN PROCEDURES CAN CREATE A CENTERLINE TRACK WITH RANGE CHECKS

With the use of the nearly rectilinear grid system of LF/VLF coordinates, several of these serious (VOR letdown) limitations are overcome (see Figure 4).

1. The "waypoint selection" is a waypoint to the end of the runway using LF/VLF.
2. No DME is added either to the ground or the aircraft.
3. We will have effectively a DME (along centerline) capability, giving continuous longitudinal checks of position so altitude corrections can be made rather than only one vague initial altitude check at the time of the beginning of the descent.
4. Probably most importantly, the non-precision approach flight-track is parallel to and on the centerline of the runway, avoiding a $\pm$30-degree heading change and track error at MDA up to 4,000 feet.
5. Approaches can be made to any runway. Since many such small fields have cross-wind runways that are useless in low ceiling weather as they do not meet anything but the circling criterion, a criterion even more hazardous and with higher limits than our 30-degree, 6 NM criterion. At cross-wind runways using LF/VLF, straight centerline approaches can be made to four thresholds with an equivalency of DME on each, greatly reducing the approach minimums at that airport, since the positional breakout "scatter" at MDA will be reduced by a factor of as much as 10 times, permitting a continuation to land under visual conditions.
6. Simple computations can be set up, by the pilot turning two knobs or so to create a path in space something like a crude glide slope, using one of the many VLF/LF LOP's that cut across the flight track (localizer track) to the runway. This can give a distance to go tot threshold to an accuracy of about 1,000 feet or perhaps even 600 feet (according to Navy "Rendezvous" tests with Omega), since the runway coordinate values are derived by an LF/VLF receiver in the local area referenced to the end of the runway. This difference

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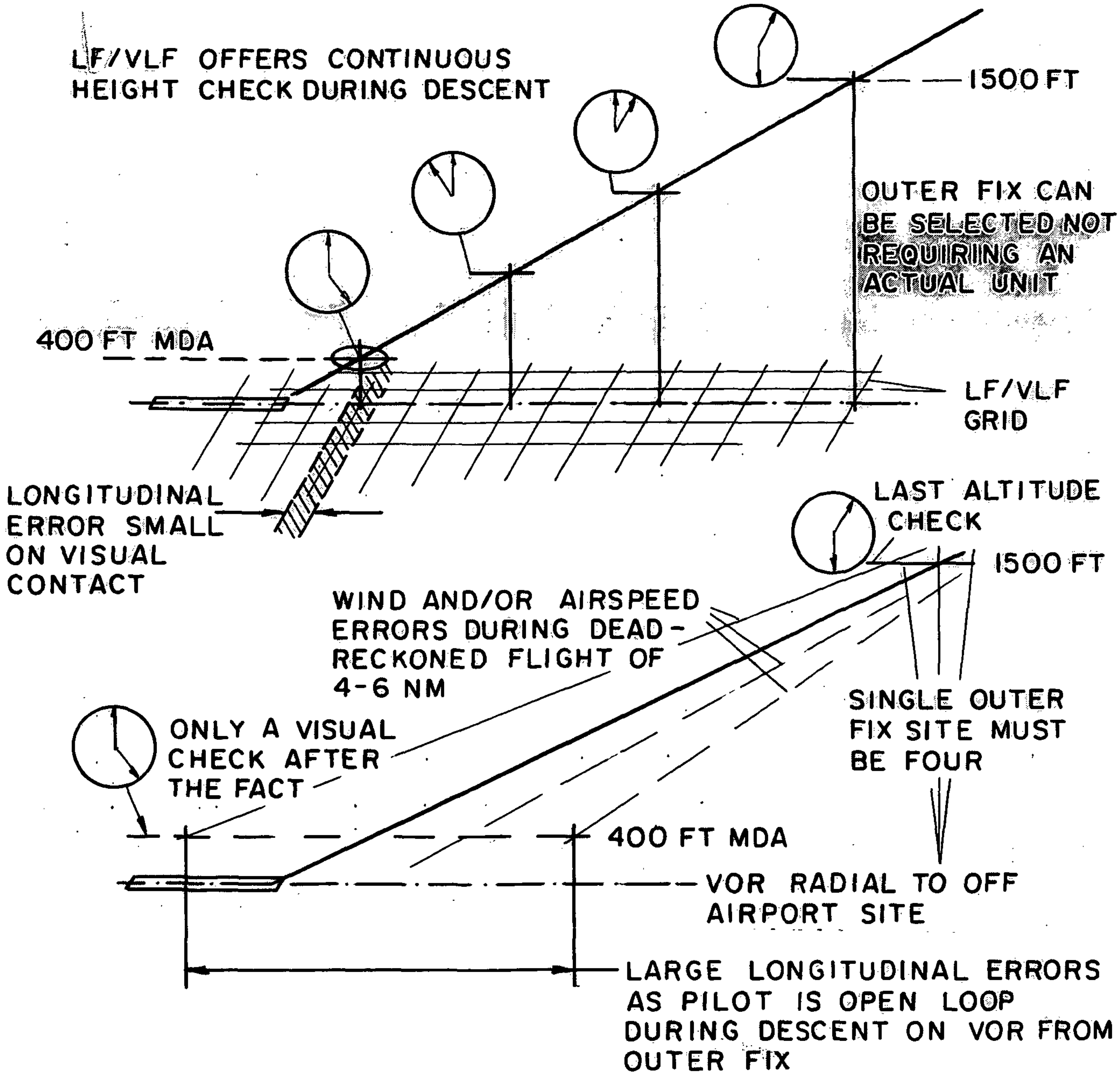

FIGURE 4 LACK OF LONGITUDINAL CHECKS ON ALTITUDE ON VOR NON-PRECISION APPROACH IS A POSSIBLE CAUSE OF MANY RECENT FATAL ACCIDENTS

in value is continuously supplied with barometric altimeter data to avoid any diurnal errors or pilot errors (see Figure 4).

This VLF "differential" VLF/LF receiver, essential to our concept, may cost about $5,000, because it does not have to "track" at a given velocity but merely measures statistically the precise position of the end of a runway in terms of the LF/VLF coordinates. One such receiver might serve a radius of about 50 to 100 miles since the differential corrections from a fixed, surveyed point (receiver location) are highly predictable. When, say, 1,000 such receivers are produced after R & D, the cost of a $5,000 receiver is shared with perhaps 10 small airports that could be served with a single, differential receiver. An average cost per airport of about $500, including some simple telephone circuits, would be the only additional costs to an existing small airport for a possible 400 and one mile or 300¾ certification.

If, for example, a general aviation aircraft descends from a fix on a VOR radial toward the runway which is some 5 NM distant, typically about 3 minutes might elapse during the descent period. In addition to a rather poor fix at the beginning with errors up to 1 NM being typical (such as using a more distant VOR for a crossing fix), vertically dead-reckoned flight ensues until the airport is observed beneath the cloud limits. During the letdown following the VOR radial, unknown winds or airspeed errors can cause the actual position in space to vary. Most approach charts give time in seconds from the last fix as a means of estimating the correct altitude (see Figure 5).

For example, an unknown head wind of 10 to 15 knots could cause the aircraft's path in space to be steeper, arriving at the 400-foot MDA about a mile short of the planned contact point. Or, if it were a similar unknown tail wind this would mean reaching a 400-foot MDA about a mile beyond the threshold, possibly overflying the runway and forcing a circling approach, a most hazardous procedure, since the runways we are considering are usually 5,000 feet or less (often even under 2,000 to 3,000 feet).

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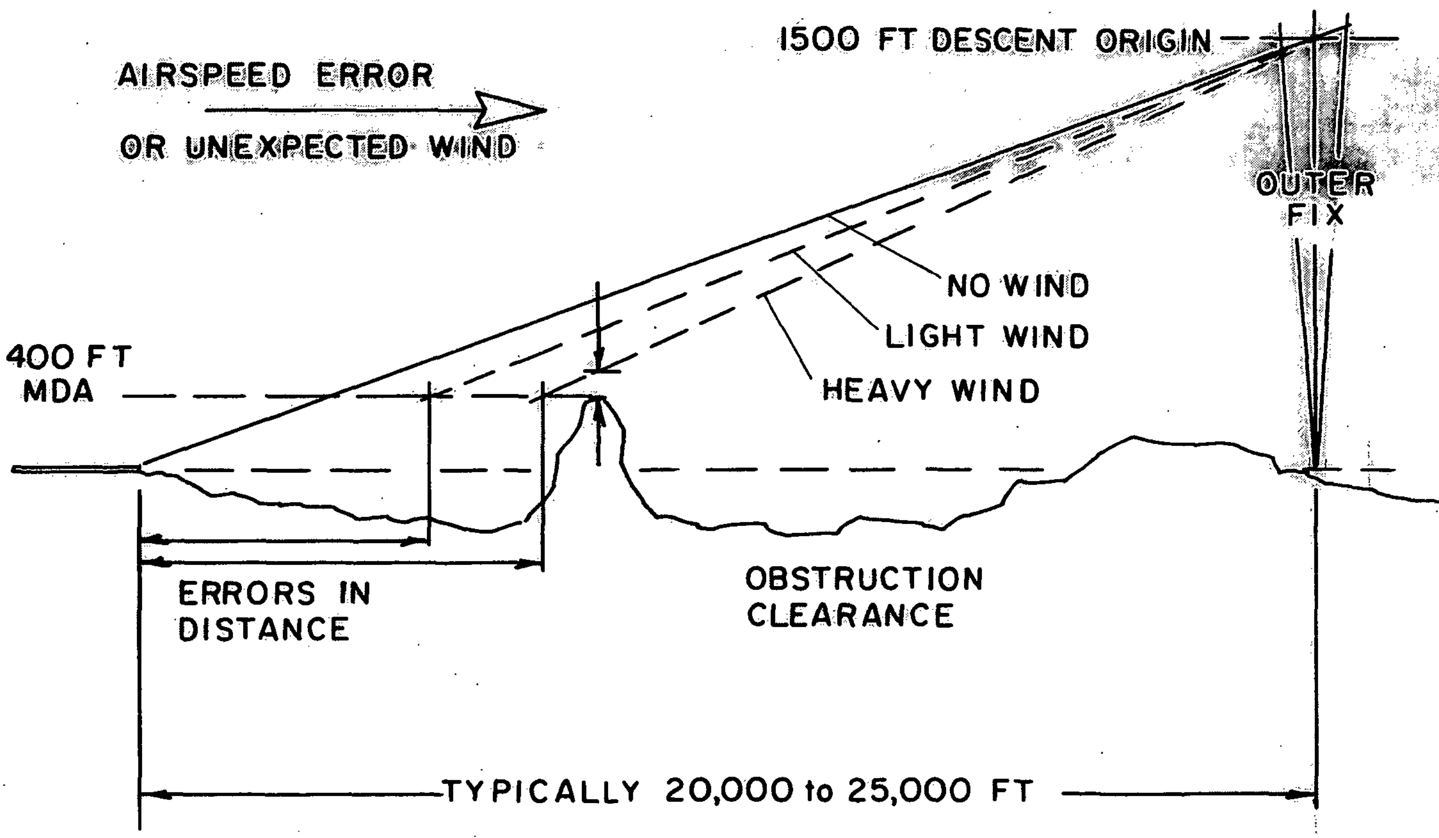

FIGURE 5 VOR LET-DOWN PROCEDURE IS OPEN-LOOP IN DISTANCE FROM DESCENT FIX, CAUSING INCREASING ERRORS AT MDA THAT MAY VIOLATE OBSTRUCTION CLEARANCES

Other sources that can contribute to this error at the MDA are the barometric altimeter, its use, its setting, or the input data from a remote surface reference point (typical of small airports). Simple geometric analysis will show why so many collisions with the ground often occur in such procedures, since the pilot is actually descending into the altitude region containing obstructions. With the LF/VLF coordinate system, there are (any airport in the United States) at least four lines of position (LOP's) so that two pairs of LOP's are used to compute a course parallel to the direction to the centerline and coincident with the centerline. Another simpler computation determines the distance to the threshold (often called a way-point). This system, using a low-cost receiver, offers a continuous indication of distance to threshold--that is, a permanent ground referencing system exists at all airports with no local installation other than a possible reference ground receiver to supply exact coordinates to the pilot. The approach is not "open-loop" as is now encountered longitudinally in VOR letdowns.

The longitudinal coordinate, let's call it the DME coordinate, is as accurate as the other, which is equivalent to a localizer, both being about 500 to 1,000 feet in accuracy. Thus, we can define the threshold to about $\pm$1,000 feet or maybe even $\pm$600 feet according to some data. This terminal condition at threshold or way-point is shown as a distance to touchdown and is employed then with the barometric data to give a safe descent path as compared to VOR (see Figures 4 and 6).

G. SUMMARY OF A NEW 400 AND A MILE NATIONAL AVIATION SERVICE

Essentially, we can eliminate most of the deficiencies and hazards of the VOR letdown (non-precision approaches) as well as the costs of hundreds of more VOR stations. The LF/VLF system avoids the angular intercepts; its tracks are all parallel to the extended runway, avoiding a serious turning and psychological orientation problem when breaking out at 400 feet (see Figure 6). A DME-type function is realized for free using the same LF/VLF receiver-processor as used for centerline. Outer fixes can be

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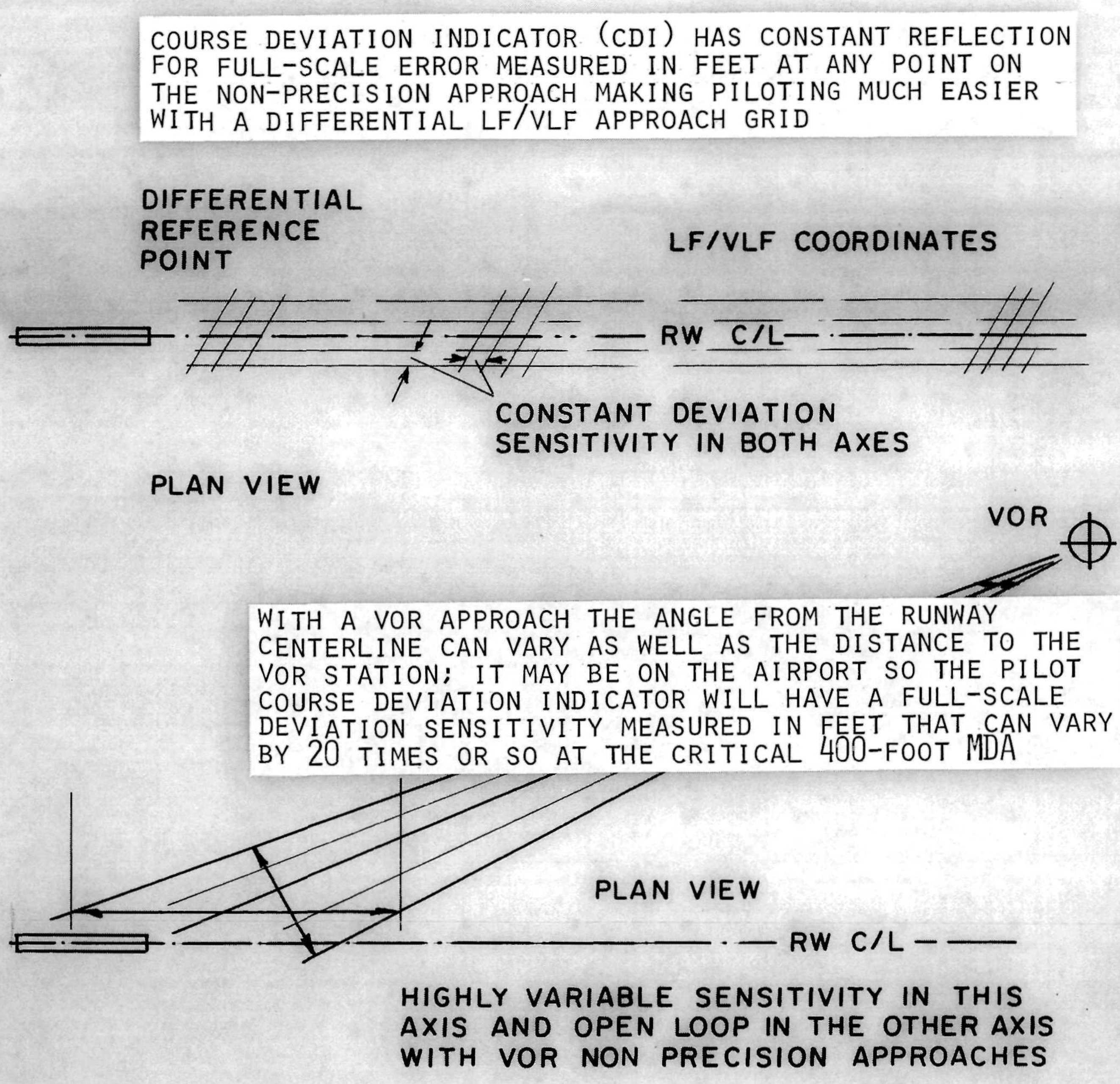

FIGURE 6 PILOTING PROBLEMS INCLUDE VARIATION IN SENSITIVITY OF THE COURSE DEVIATION INDICATOR WITH VOR (WHILE IT IS CONSTANT). WITH LF/VLF PILOT IS OPEN-LOOP LONGITUDINALLY IN VOR, AND CLOSED-LOOP WITH LF/VLF

eliminated as well as probably many markers and superfluous VOR stations. The pilot will obtain what is an equivalency combination of DME, VOR, course line, precision altitude correction, etc., with a receiver only. A $2,000 cost seems likely for a general aviation unit based on at least two commercial designs now under test. Low altitude coverage and approaches to all runways of a small field are easily accommodated. A single reference receiver shared with 10 airports would prorate the only airport cost for such a service to about $500 to $1,000 per airport. The total service to 10,000 remote and small city airports of the nation can be provided with about four to six stations at LF/VLF specifically designed and installed for this purpose. Another 1,000 VOR stations needed for the 10,000 small fields to give a 400 and one mile capability nationally would cost the nation through their life cycle about one billion dollars and require new 25-kHz VOR receivers. An LF/VLF net to provide a national minimum of 400 - 1 NM at all such airports will cost a small fraction of this amount for an equivalent life cycle.

A minimum national safety standard of a simple to use, 400 and one mile capability would probably reduce the fatalities in this area of air safety so extensively as to create the savings equal to the cost of such a four- to six-station network. Experience may indicate 300¾ is also safe with LF/VLF (see Figures 3, 5, and 6 through 12). It is time general aviation be guaranteed a minimum national approach standard at all airports throughout the nation, regardless of their size. One hundred thousand users are possible.

H. USE OF AREA-NAV VORTAC

The foregoing relates to the use of a VOR-only service such as the VOR letdown procedures in the TERPS. However, modern instrumentation now allows the computation of position in rectangular coordinates from the VORTAC polar coordinate source, using the VOR receiver and a DME. Specifically, this infers the use of all 360 degrees of the VOR bearing data, not some limited and selected "clean" radial as in the past for an airway. For the analysis of Area-Nav accuracy, all angles including the worst must be considered.

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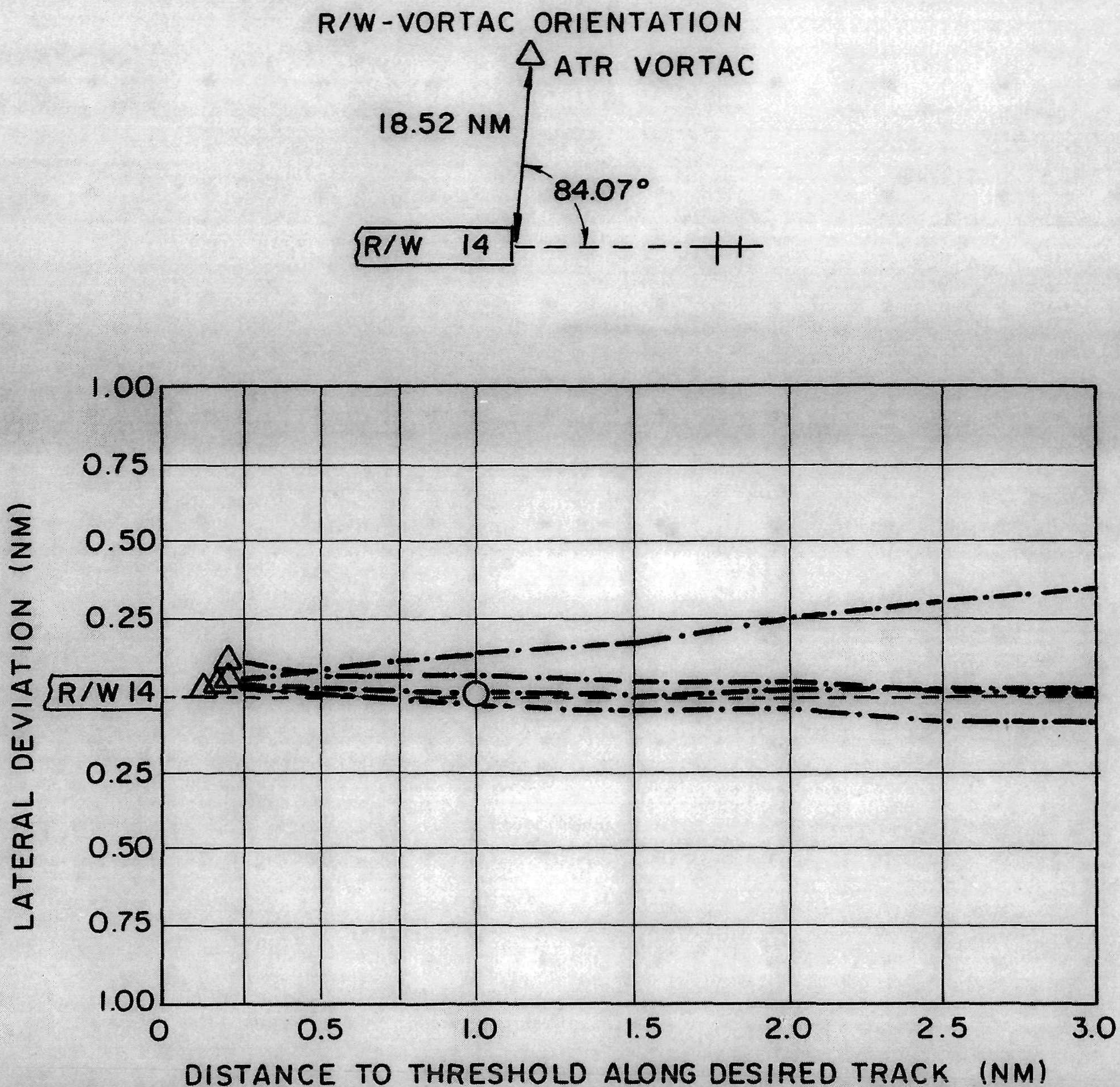
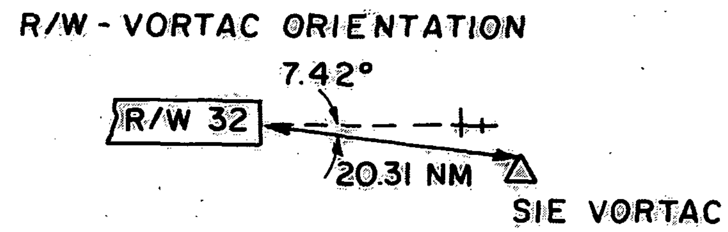


LEGEND:

- – – – – DESIRED TRACK (R/W BEARING)
- –·–·–· PILOT C TRACK
- ○ DESIRED POSITION AT 378' (400' MSL - 22' FIELD ELEVATION)
- △ ACTUAL POSITION AT 355'-395' (PILOT INDICATED FAILURE)

FIGURE 7 CAPE MAY 14-ATR ORIENTATION RESULTS (VAC 1NM FUNCTION)



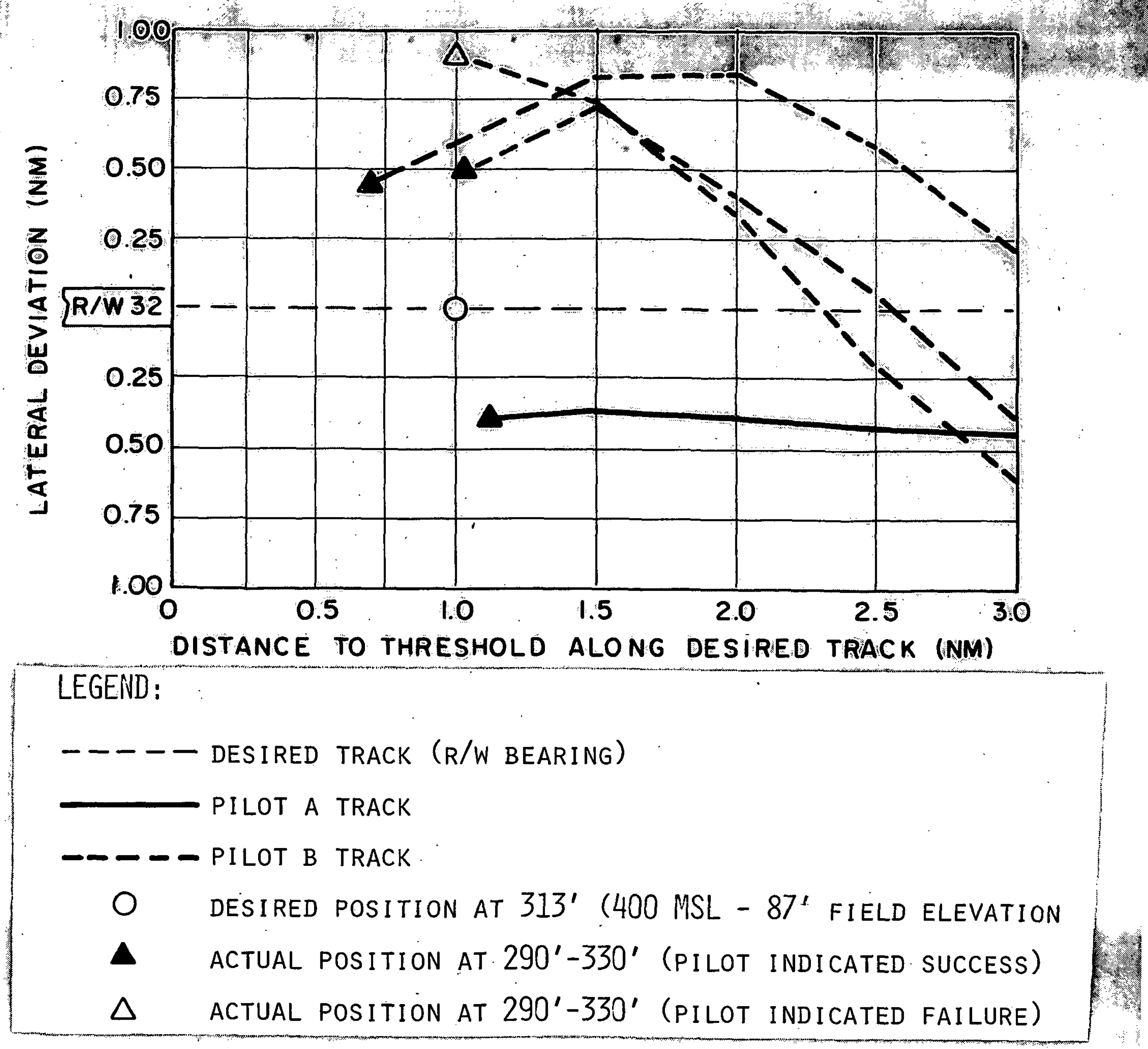


FIGURE 8 MILLVILLE 32-SIE ORIENTATION RESULTS (VAC 1NM FUNCTION)

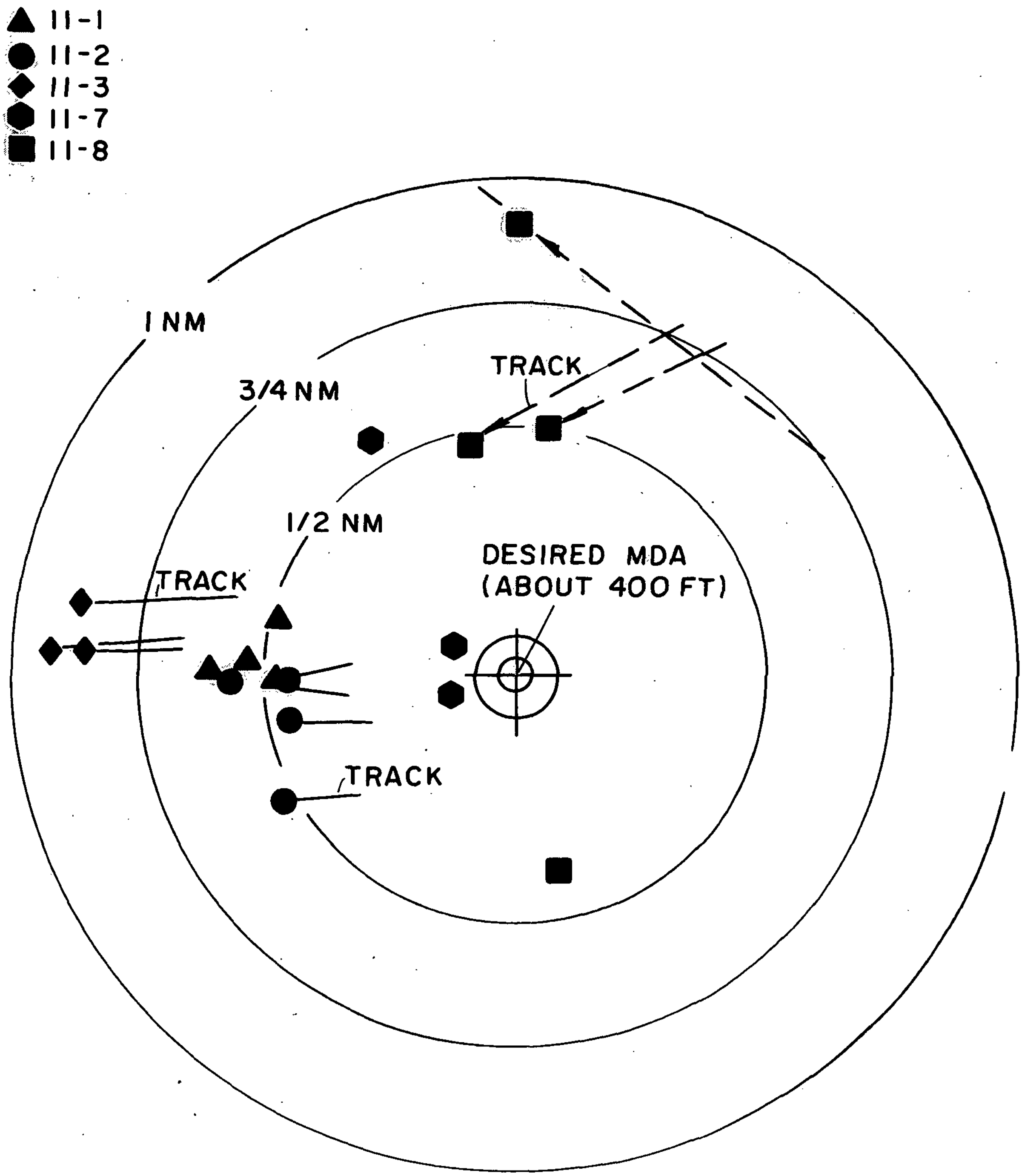
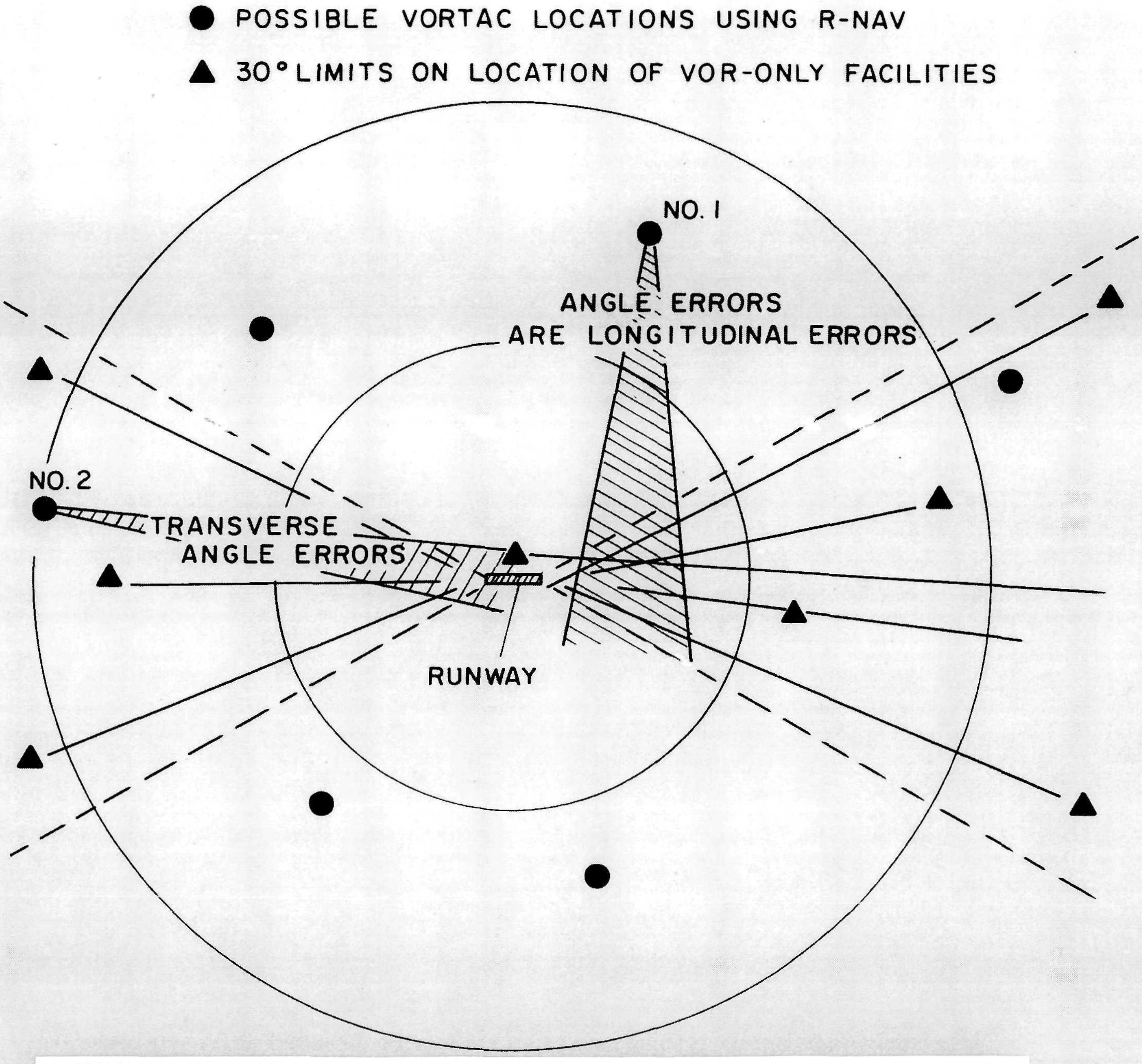


FIGURE 9 TYPICAL VORTAC ERRORS USING AREA-NAV COMPUTERS



R-NAV USING STATIONS IN ANY SECTOR ABOUT THE RUNWAY AXIS AVOID THE 30-DEGREE LIMITATION OF NON-PRECISION VOR-ONLY APPROACH PROCEDURES

HOWEVER, THE LONGITUDINAL ERROR IS HIGH WHEN IN POSITION 1 FOR THE VORTAC; WHILE THE TRANSVERSE ERROR IS HIGH IN POSITION 2 FOR A VORTAC INPUT TO AN R-NAV NON-PRECISION APPROACH

FIGURE 10 POSSIBLE VORTAC LOCATIONS USING R-NAV AND 30-DEGREE LIMITS ON LOCATION OF VOR-ONLY FACILITIES

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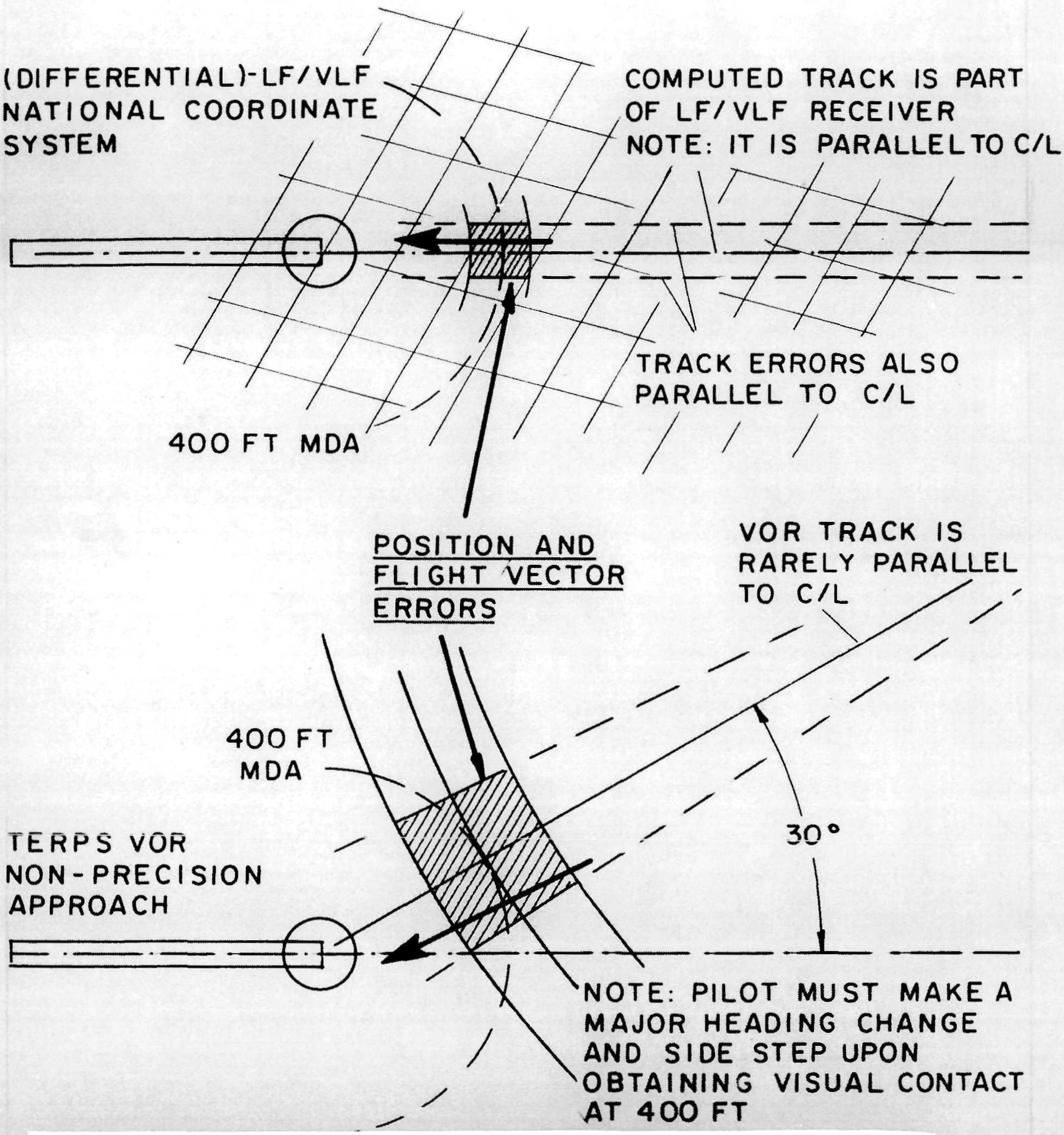


PILOT MANEUVERS ARE GREATLY REDUCED IN LF/VLF APPROACH USING RECEIVER ONLY (2 LOP'S AT LEAST) AS COMPARED WITH A VOR LET-DOWN TO THE SAME LIMITS

(NOTE POSITIONAL AND FLIGHT VECTOR ERRORS)

FIGURE 11 PILOT MANEUVERS ARE GREATLY REDUCED IN LF/VLF APPROACH USING RECEIVER ONLY (TWO LOP's AT LEAST) AS COMPARED WITH A VOR LET-DOWN TO THE SAME LIMITS

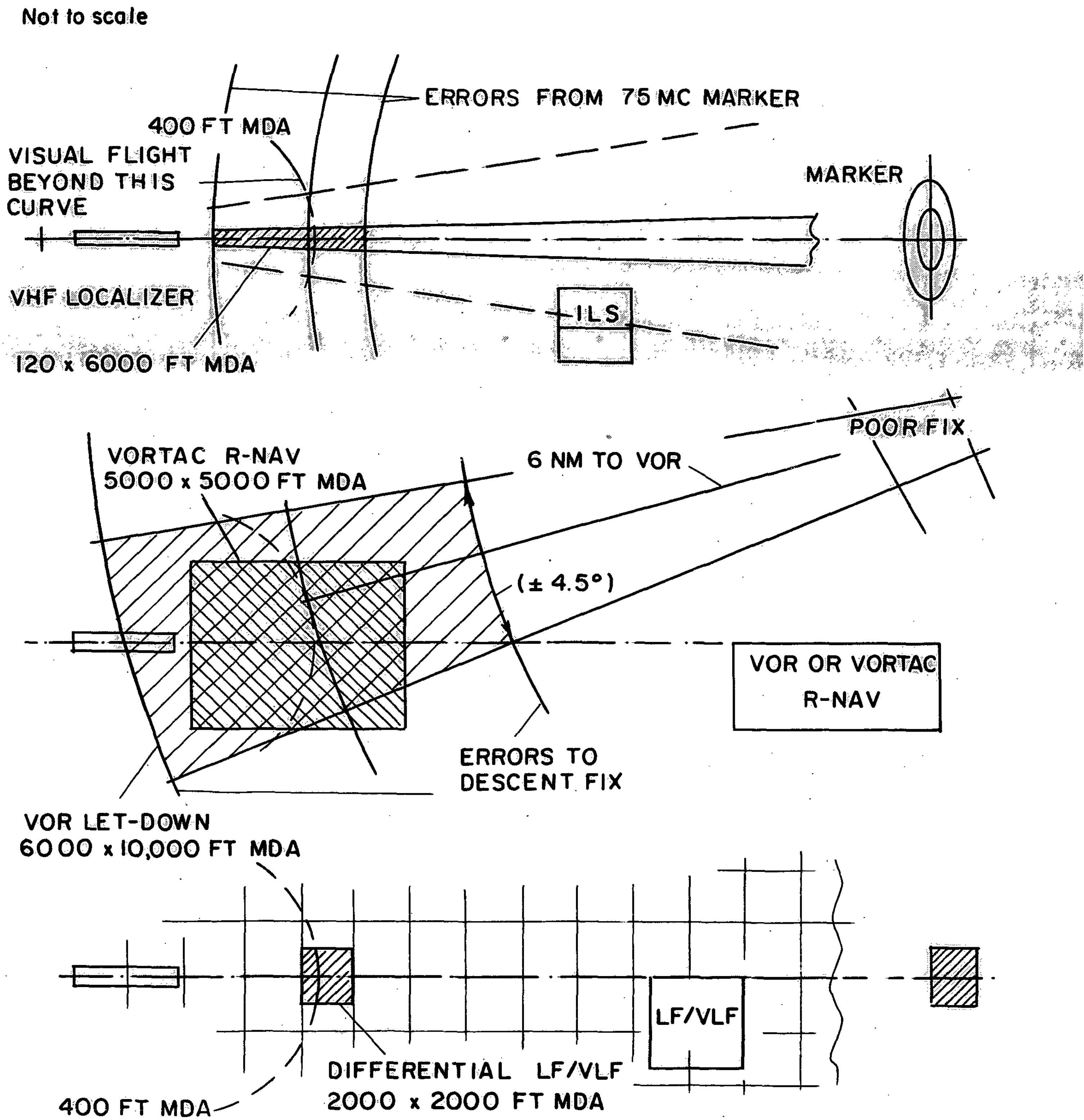


FIGURE 12 COMPARISON OF SOME TYPICAL ERRORS FOR THREE TYPES OF SYSTEMS TO ACHIEVE A NATIONAL SERVICE FOR ALL AIRPORTS AND ALL USERS OF 400 AND ONE MILE

The worst-case accuracy (maximum error at any angle within the 360 degrees of a given VOR) must now be considered for a non-precision R-Nav approach since there is no way to predict the runway displacement and heading from the VORTAC station relative to this poor angle-data sector.

The FAA has fortunately conducted some well-documented tests using the "VAC" Area-Nav computing system fed with a good VOR and a good DME airborne equipment. The "VAC" Area-Nav computer costs about $10,000 to $15,000. This cost is in addition to the cost of the VOR/DME equipments (combined about $3,000 to $4,000 more).

In the FAA report RD 70-11, "An Evaluation of the VAC Model 5-A, Area Navigation Equipment," dated May 1970, we have some measurements of these VORTAC Area-Nav errors. If the error is mostly caused by the VOR (Figure 7--Figure II-3 of the FAA report), we see that the longitudinal position of the aircraft was in error by nearly a mile, though the pilot seemed to be within 0.25 NM or about 1,000 feet of centerline. This is true because the DME is mostly controlling errors, not the VOR. Although this is shown as being "long," it indicates that the aircraft when actually at a 400-foot height would be safe, but there is no reason to believe that the VOR error could not just as well have been in the other direction, and the pilot would have been at 400 feet a mile further from the runway than his intended approach pattern or approach aim point is a mile short of the runway. This infers obstacle clearance would be the most serious hazard.

In Figure 8 (Figure II-8 of the FAA report), we see a case where the error at the MDA is mostly transverse to the track since the track is nearly along a radial (within 7 degrees of one). Here the pilot also considered the approach a failure since he was off centerline at threshold by about 0.8 mile in the worst case. This is true because the VOR is controlling cross-track errors. Since the VOR in the FAA data is about 20 miles distant and is expected to have ± 3 to 4 degrees of absolute (not averaged) error, an error around a mile of cross-track deviation from centerline can be expected. This FAA report clearly shows that "VAC" or any

other R-Nav computer with VORTAC inputs will not correct basic VOR errors.

Admittedly, two poor examples were selected in the FAA report (there are others with less error). However, these are still representative of a much broader source of data too voluminous to publish. These FAA records make the point quite clearly that the approach threshold or MDA error is variable for every VOR, at every angle of the VOR, every geometric disposition of the VOR relative to the runway distance direction, etc. This is to say, there is no uniformity in VORTAC R-Nav errors, and one must consider the worst cases, not the best cases, when considering VORTAC. Since the threshold MDA errors vary by as much as 20 to 30 times in determining where the pilot actually is when he is at 400-feet altitude, a ±1 NM is probably the extreme, according to Figure 9.

The pilot cannot be expected to be aware of the amount and direction of these errors. All he knows is that when he uses a VORTAC R-Nav computer, he is at the mercy of the computer output. Although it may be damped and "smooth" it is impossible to extrapolate the varying errors relative to the amount of radial or cross radial motion with respect to the VOR. The final Area-Nav indication is usually a display like a localizer that is about ±1 NM wide (or a 12,000-foot wide track whose center may be off an equal amount). It is questionable to claim that R-Nav based only on VORTAC will give an "ILS equivalency" at all non-instrumented runways. It may come close occasionally where a VORTAC is actually on the airport. But when sited off the airport VORTAC accuracy is greatly reduced in centerline performance as compared to a centered, standard localizer. It is quite unrealistic and misleading for the sales promoters of R-Nav to make such claims for VORTAC's up to 20 miles distant, or maybe 5 to 10 miles distant, which are the usual cases at small airports.

One cannot use "RMS" or other smoothing criteria normally used to quote VOR accuracy. A 6-degree error, although only appearing in a small sector around the VOR, may be lost in the RMS value, but it is still 6 degrees if it happens to lie along or near a computed Area-Nav track to a runway. The FAA report (noted above) clearly points this out. A combination of a few of the

error figures into a single scatter diagram is shown in Figure 9 and gives some idea of the distribution.

As can be expected, one should allow at least ±1 NM for the use of VORTAC with or without R-Nav computers when any of the many thousands of combinations of runways, runway directions, and VORTAC's, all taken on a national basis, are considered. If, for example, it was decided that no airport with a 400 and a mile authorization would be greater than 6 miles from a VORTAC, then we would have a VORTAC in every direction spaced about every 12 NM, or a total of nearly 20,000 VORTAC's nationally. Even so, at 6 NM we see (Figures 2, 3, and 12) that a typical operational error spread is about 5,000 feet, and in worst cases of poor VOR sites, this may be as high as a spread of 7,000 feet. This must be compared with an LF/VLF system that does not have angular errors or angular dilution. With a differential LF/VLF system, either a local or national diurnal correction signal can be used as all coordinates are shifted, not just a few selected ones. This is to say, there is no standard VOR error curve that can be used for correction of specific VOR signals as there is with LF/VLF. With proper engineering of a new national LF/VLF aviation system, probably about 1,000 feet of accuracy could be realized everywhere (see Figure 11).

The LF/VLF errors are uniformly predictable across the nation, being the same value for an airport 30 miles from a VORTAC as one with a VORTAC on it. It is almost equivalent to say differential LF/VLF is as useful as a VOR on every small airport or strip. The LF/VLF coordinates are wide-based (1,500 to 3,000 NM), hyperbolic lines, lying on a sphere that converts them to essentially parallel lines crossing at oblique angles for any local area (an area equivalence of a single VORTAC coverage). Essentially, oblique parallel lines exist at any altitude from the surface to well over 20,000 feet, giving a three-dimensional rectilinear system avoiding the R-Nav curvature of a VORTAC station. The aviation LF/VLF system herein discussed can be engineered and installed for about 10 percent of the costs of the current 2,000 stations (about 1,000 VOR's and 1,000 TACAN-DME's).

V. COST COMPARISON OF LF/VLF-VORTAC SERVICES FOR A NATIONAL 400 - 1 NM SERVICE

We see that with the normal TERPS "VOR let-down" (non-precision approach to a 400-foot and 1-mile MDA, very serious constraints exist because of VOR deficiencies. A high risk level is also evident in the accuracy analysis as witnessed by several recent accidents (in, say, the past 4 years). This type of approach has been identified by ICAO as probably the most critical area of air safety. Next we see that even with costly VORTAC computers, the approach tracks can be computed and displayed along the runways, avoiding the 30-degree legs crossing the runway axis. However, the computed VORTAC displacement errors run as high as nearly 1 NM in any direction from the MDA three-dimensional aiming point. An FAA test of a few VORTAC sites confirms this limitation. The cost to the nation to meet the close-in VORTAC means that stations would have to be within 6 NM or less of the small airport, the STOL airport, etc. To assure full growth and public use potential to general aviation, a minimum national service should be available. To carry this analogy to the extreme, one can assume that ten thousand small airports of 1980 would cause the need for ten thousand VORTAC's to obtain 6 NM spacing. Channelization changes of VORTAC add costly new airborne units to the total national cost.

This cost is about \$1,000 to \$2,000 for an improved VOR receiver, for a DME, and about \$3,000 for a simplified R-Nav computer, and about another \$1,000 for displays. If equipment fails we cannot "recover" by flying a radial to the VOR station, so the regulations will probably require a dual VOR or dual DME. Installed we have an airborne investment in VORTAC of about \$7,000 to \$8,000 to provide the minimum ability to approach an airport under conditions of "400 and one mile." This is the cost to each aircraft to provide the minimum IFR capability to a non-equipped airport (without ILS, radar, etc.).

With a \$2,000 to \$3,000 multi-LOP Omega type (LF/VLF) receiver (using a "U.S.-only" grid with higher accuracy and update rates than Omega), we can insert the threshold coordinates and the

initial descent coordinates and provide the pilot both a lateral and longitudinal deviation from a selected approach track (that is aligned with and parallel to the runway centerline). Furthermore, the pilot is provided a "distance to go" meter which is a meter movement giving anticipation to the threshold "way-point," or an equivalency of a "DME for free" on every airway in the nation (see Figure 12).

From these two simple displays, the pilot could use a simple table (probably actually a part of the display) showing his distance from threshold and the correct barometric height for that distance. This is similar to a glide path and could be so displayed. It is also strongly suggested that some means be added to calibrate barometric altimeters in the vicinity prior to beginning of the descent as FAA (DOT-ATCAC) reports suggest errors as much as 400 feet exist in general aviation units. This vertical height correction is another subject not covered here but of utmost criticality to the success of all of ATC, not just the approach to land. The third dimension of ATC requires much more attention. Without a safe means of using the third dimension, ATC will have many difficulties. Solutions using vertical crossed-beam radars have been proposed that would give the service to pilots on voice channels at no cost to the pilot.

VI. SIMPLIFIED PILOT USAGE OF LF/VLF SYSTEM OF NAVIGATION USING "BROADCAST CONTROL" CONCEPTS

Some momentum toward the use of LF/VLF techniques for aircraft navigation and traffic control is now evident. The recent (Nov. 9-11, 1971) Omega Conference (reference 18) held by the Institute of Navigation (ION) in Washington, D. C., saw some 400 experts assemble and present papers on nearly every aspect of the Omega system. Three significant LF/VLF aviation possibilities exist: (1) use of Worldwide (WW) Omega; (2) use of an "Omega-like" system optimized for aviation use in the 48 contiguous states; (3) a "mix" use of (a) WW Omega and VOR, (b) U.S. Omega and VOR, and (c) U.S./WW Omega. Fortunately, at very low cost these possibilities can all be tested with the current plans for WW Omega.

WW Omega is an 8-station complex that serves the air and surface regions of the entire world with at least three Lines Of Position (LOP's) everywhere. By using three frequencies the diurnal and other LOP shifts are greatly reduced by heterodyne methods, such as "Composite" Omega, extensively tested by J. A. Pierce of Harvard University. The technical papers from the conference and hundreds of previous publications suggest that the Low Frequency navigation has a great deal to offer aviation users.

It was reported that Russia has introduced an LF navigation system of its own operating near the 10.2 and 13.6 kHz frequencies of Omega (reference 18). A previous study (references 19 and 20) has suggested a similar move by the United States wherein the 48 contiguous states would be served by a four-station net (or "chain"), giving several improvements over WW Omega--primarily cost reductions and freedom of international political changes since only two of the eight Omega stations are on U.S. soil (North Dakota and Hawaii). However, it was reported by the U.S. Coast Guard (and other national authorities) that Omega would be fully operational with greatly improved, new, high-powered stations by early in 1974. The detailed pictures showing the construction status of the Japanese station added considerable credibility to this schedule.

Because of other trends (reference 29), general aviation may be the first large aviation user of WW Omega signals. The possibility of a supplemental VLF system for the United States does not imply that WW Omega will not be adequate, but that for many reasons this useful experience will undoubtedly lead to a U.S. national LF/VLF system such as the Russian reports indicate became desirable to cover several unequipped parts of the nation and to optimize signal levels, etc. The Canadians are also very interested in such ideas as only the most southerly portion of Canada has VORTAC airways. The majority of Canadian airspace is too thinly populated with air traffic to warrant any expansion. Because VORTAC is too costly for large regions of coverage, such as, say, an area 2,000 by 3,000 miles, aviation's hope must rest with these techniques of LF/VLF navigation and traffic control.

A. WORLDWIDE VS LOCALIZED OMEGA

Currently so much attention is focused on the enthusiasm for the worldwide use of Omega as the first radio and only navigation system to be readily available anywhere. Often the problems associated with this global use are carried to general aviation, and many suggest Omega receiving techniques and navigation techniques will be too complicated for the general aviation pilot, adding too much workload, control settings, etc. This need not be so with good design of a low-cost general aviation receiver. Since the pilot workload using VLF navigation applied to general aviation is of concern to many private and government authorities, it needs some examination.

We will start with the simplest use, only in the U.S. National Air Space system, and only use by general aviation. Here we deal primarily with the single-engine/light-plane owner, who operates over short distances and into remote fields; his aircraft is not pressurized so it is operated below, say, about 10,000 feet. The only fair measure of pilot workload to be made is by the comparison of LF/VLF usage with the usage of existing VORTAC system.

The goal is to provide the same equivalence of data as that furnished to the pilot. With VORTAC we deal with many separate systems that have characteristic VHF limitations. For

example, at critical low altitudes of interest to general aviation, the line-of-sight coverage of VORTAC is about 10 to 50 nautical miles. This service area depends upon intervening terrain, which in many instances limits the low altitude coverage to considerably less. With trends of "keep them high" (reference 27) in FAA terminal areas, the airlines tend to stay about 4,000 to 5,000 feet, leaving general aviation between about 1,000 and 3,000 feet--a current trend toward vertical segregation.

It seems equitable to both systems if we now compare the use of Omega or LF/VLF navigation to VORTAC on the basis of, say, a 100 by 100 mile square. A fair assessment can then be made of a general aviation pilot's workload, and other problems that may be related.

To begin with, both systems are "differential" in their use by the general aviation pilot operating the light single aircraft. "Differential" means that he must tune to locally referenced navigational signals to obtain enough information to use the coordinates. If it is a case of VOR-only usage, the pilot must know approximately where he is located first in order to tune to the right VHF channel as most of the nation's VOR signals will be beyond his immediate line-of-sight. Once he tunes the VOR station "in" by assuming its approximate location in its selection using the radio frequency as the "station-identifier," he must assure himself that the channel selector or his operation of the dials did not select the wrong channel or the wrong VOR station. Occasionally, channels may even be shifted by the FAA. This assurance of the local reference is accomplished by listening to the audio output of the VOR (be it a voice or Morse code). The identity of the VOR is then established, and the chart establishes the expected VOR differential signal.

Next our subject pilot (using the VOR-only system) must select or measure the radial he is actually on by turning the course selector knob. When the course deviation indicator (CDI) needle passes through zero on the analog right/left deviation indicator, the course (or its reciprocal) is then evident. A "to-from" indication resolving direct or reciprocal bearings must be observed

by the pilot before he can bracket and fly the radial. He may desire another radial rather than the one he is on, so must select this also.

Not knowing his exact distance from the VOR (without DME), he must now obtain some "cross-fixing" data, such as tuning to another VOR station to obtain an approximation of his location on the VOR-radial-LOP emanating from the ground position of the selected VOR station. With these several manual operations by the pilot while in flight, and while continuously referencing the OBI and CDI to a chart, it is then possible to fly along the radial to or from the station, toward some destination. Destinations are seldom VOR stations, thus, varying the selected radial when passing over the station is commonplace.

If the destination is near the signal limits of the first VOR, it will then be necessary to select another VOR station going through most of the same procedures (cockpit workload) as noted above. To proceed requires continuous selection of various factors as the VOR LOP's are traversed. It is likely that the two radials from the two adjacent VOR stations that would align themselves to make a continuous path indication (CDI at zero) will not align smoothly with one another, since VOR errors of 3 to 4 degrees are common. If one station emits its radial in error in one direction (plus 3 degrees) and the other station has an error in the opposite direction (minus 3 degrees), then the indicated spatial track could shift by as much as 3 to 4 miles (say 40 miles from one station and 30 miles from the other). This is disconcerting to the pilot and emphasizes the discontinuous nature of VOR signals and the difficulty of using them in a single-pilot, single-engine aircraft where all the cockpit workload is concentrated on a single person rather than shared as in most airline operations.

With no basic master plan for VOR stations that is easily remembered by a pilot and no plan that relates either to adjacent frequencies or adjacent station locations, the pilot must be continuously referring to VOR charts to proceed. This is to note that the many hundreds of VOR stations are not laid out or aligned on any basic "grid-plan," as, for example, a rectangular grid plan with a VOR at each crossing of the grid.

Nor are the radio channels arranged so that consecutive stations have consecutive frequencies. Random processes seem to have been employed in the configuration of the nation's VOR system. Consequently, the pilot must fly a series of VOR legs (or radials) that wander in the general direction of his destination but may vary in heading by tens of degrees from one VOR radial to the next VOR radial because of the local terrain, airway restrictions, etc., but mostly because of the random siting of VOR stations and the inability of the pilot to use some simple mental processes or rules for preventing this high workload. VOR and VORTAC are very complex to use and create many pilot restraints. The VOR or VORTAC cockpit workload is unnecessarily high.

The addition of DME to VOR helps in some respects but complicates the combined use in other respects, since the DME signals must also be identified, and the pilot must assure himself that the DME is from the same origin as the VOR. Fortunately, "cross-channelization" tie the two together. DME coverage is not always consistent with VOR coverage, depending upon the location, terrain, specific airborne units, VHF and L-band aircraft antenna placement, etc. Vertical lobes of the ground station are the largest contributor to the lack of coincident VOR-DME coverage. L-band has 10 times as many deep nulls as VOR in a given vertical angle, etc. Thus, when both are essential, the coverage may not overlap. If now the costly Area-Nav (R-Nav) computer is added, we further burden the pilot with all the foregoing workload of VOR-DME usage, but he now must determine and set in his "way-points" (usually two of them) and fly an "R-Nav" airway rather than a radial airway. The advantage of R-Nav is that at least the origin-destination of the flight plan can be inserted. Such a flight might utilize, say, 3 to 4 radials in 3 to 4 different directions to approximate it, but can now be approximated with a straight line eliminating the "dog-legs" created by VOR-only type of track flying. The pilot must, however, continue to change stations and waypoints, since each VOR creates a new set of waypoints that must be set in even though the spatial track itself is straight. Thus, less distance is flown, and better ATC procedures accrue, but R-Nav-VORTAC workload is still high for our single pilot general aviation aircraft.

Moreover, the line-of-sight VHF-UHF coverage may now suffer at lower altitudes, since the airway is not to and over the station. Say the R-Nav track is 30 miles to the side of the station (closest tangency is 30 miles), this places the aircraft at the maximum line-of-sight distance from the VORTAC station sooner than if only a radial were flown. Consequently, more station selections, station identifications, and more setting of waypoints are added to the workload. VORTAC-R-Nav, though adding some ATC and direct routing advantages, does add considerable workload to the single pilot flying a light aircraft.

B. COMPARING VORTAC AND VLF/LF PILOT WORKLOAD

With the LF navigational coordinates of an "Omega-like" system, there is first no radio channel selection required since the entire nation's coordinates are only a single permanent setting for carrier frequencies. All three LF frequencies are used continuously and have equal coverage throughout the United States without vertical lobing or "cones of silence." The LF airway charts must still be referred to, just as in the VOR case, and the pilot must initially have an approximate idea of where he is (within about 72 NM) to set in other data.

The availability of this location is more likely in the case of LF than VOR, since even on the surface the pilot can obtain a positional measurement on VLF, something usually impossible with VOR. The VOR signal, if from an off airport station, is too weak, or if from a VOR on the airport, the signal may be contaminated by hangar reflections. LF coordinates on a runway are as useful to the pilot as at 2,000 feet above the runway, there usually being little change in signal characteristic of VLF navigation. Next, the local "differential" setting is obtained with the same voice transmission that the pilot must make to obtain the local barometric pressure setting. Barometric data is essential to either VOR or VLF navigation during IFR flight, so that the "differential-Omega" data is added to an existing network of data transmission to the pilot. This replaces perhaps the workload of station identity. The pilot may forego the differential VLF data

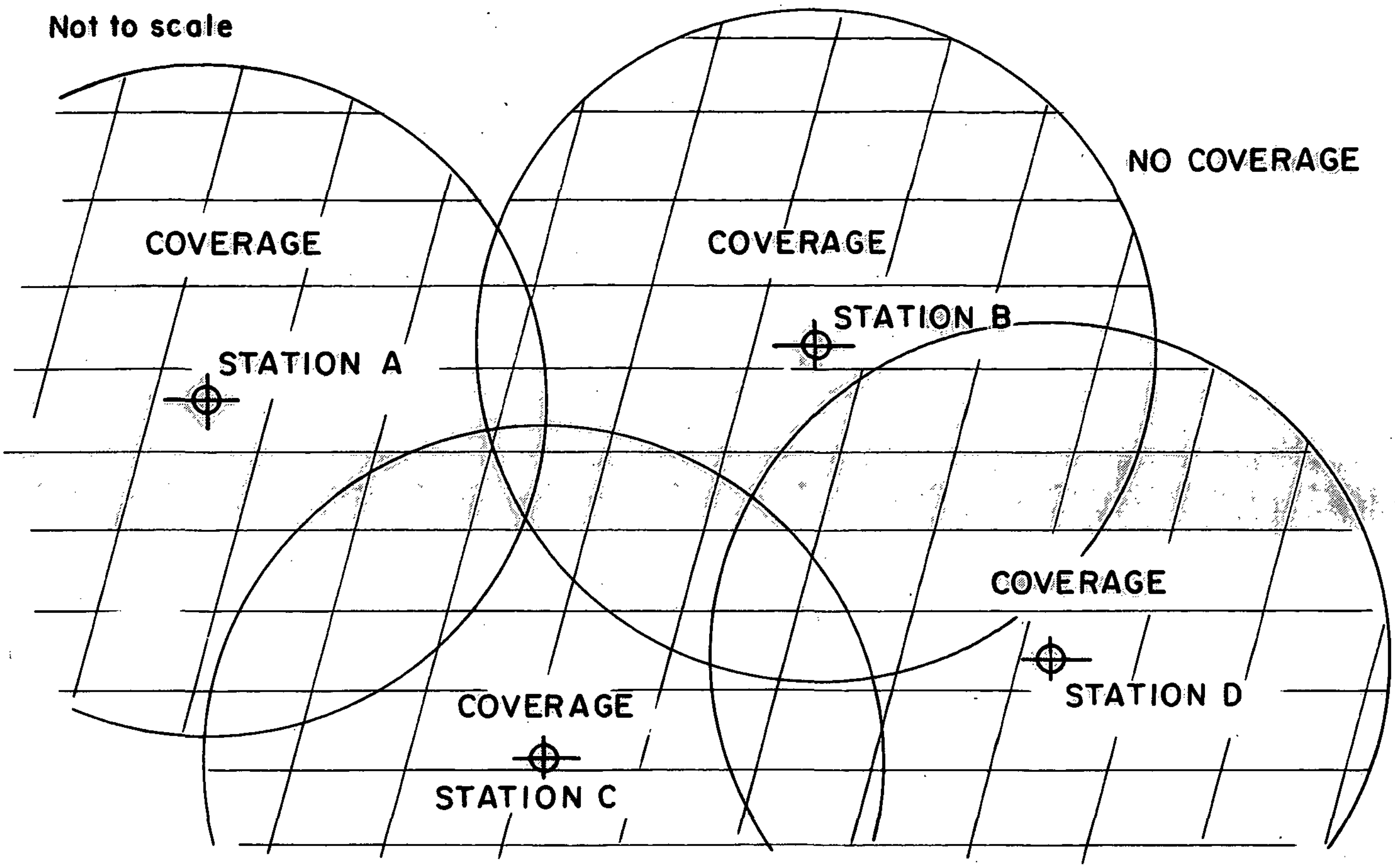
because he can achieve the same results or "zero" out diurnal effects while on the ground prior to takeoff.

The oblique-parallel nature of the Omega coordinates should provide the greatest step toward simplification of pilot workload. The pilot can easily envision his current position in VLF coordinates because the mental effort is much less. Also more easily detected in Omega coordinates is the position of his destination and how he can get there. Contiguous parallel lines are much simpler than radials from random points. Essentially, parallelograms or rectangles are much easier "graphics" to envision and to manipulate by the pilot than randomly located spherical coordinate systems of VORTAC.

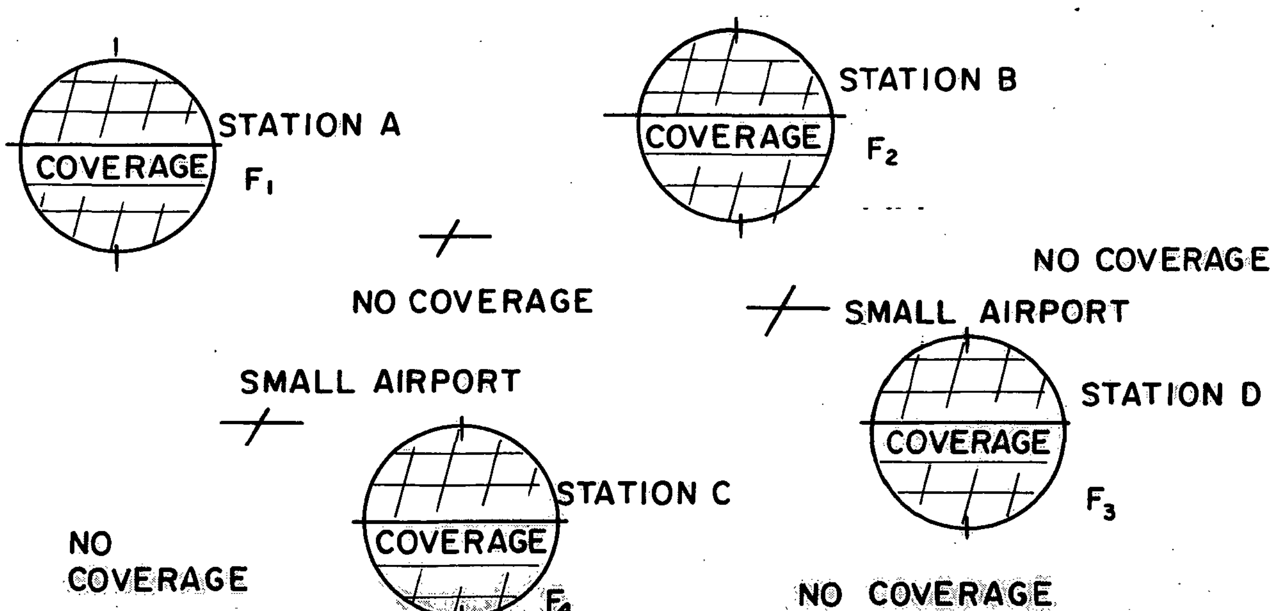
Thus, the pilot now selects his coordinate positions since he has in Omega, by reception only, the equivalence of both VOR-DME. Thus, he has a full set of crossing LOP's everywhere, with the single selection of the Omega channel for the entire nation--not 1,000 stations with 1,000 locations and 1,000 frequency allocations (Figure 13).

The differential input of Omega may simply come by the pilot's reception of Omega while on the ground, and his insertion of the destination coordinates, or from several local differential signal sources while in flight. ATC may also provide this data since the controller's view of the SSR target and its identity can be conveyed in Omega coordinates to a pilot. Such an input is good for about an hour. Several self-correcting differential techniques will probably be used by the pilots, including voice from VOR sites and the use of VOR and Omega, one checking or extending the other. The differential data is in terms of one LOP (say an E-W one), and the other LOP (the second LOP) is a N-S one. He notes the two LOP's which cross at his destination. By inserting these destination LOP's, the pilot can take off and fly on a straight line to this new location.

If the FAA has specified Omega airways or lanes, he can follow them directly. They need not be "raw" Omega lanes, since neither of the two crossing LOP's may go in the desired direction. The computation of rectilinear or "oblique-parallel" LOP's is the simplest of navigational computation.



VOR HIGH ALTITUDE COVERAGE OF FOUR STATIONS (A-D)



VERY LOW ALTITUDE COVERAGE OF SAME VOR STATIONS AT, SAY, 100 FT TO ASSURE A SOLID 400-FT SIGNAL FOR A 400-1 OR A 300-3/4 DECISION ALTITUDE

FIGURE 13 VARIATION IN VOR COVERAGE FOR APPROACH

No altitude correction is needed for the use of VLF navigation. Individual station elevation is of no consequence as it is in VORTAC R-Nav. The latter difficulty of VORTAC can be envisioned if a station is, for example, at sea level and the pilot flies an off-set airway of about 2 miles tangency at 10,000 feet. The actual slant range at the point of tangency is about 1.4 times the desired off-set tangency distance, causing the aircraft to fly a curved track, curving in and then away from the station near the point of tangency. Similar problems exist between adjacent VOR sites particularly where widely differing elevations exist and high altitude flight is desired. The spherical coordinates of the two VORTAC stations must be offset by the three elevation values: (1) aircraft, (2) VOR-A, and (3) VOR-B.

C. LANE AMBIGUITIES

The complaints about lane ambiguities are always raised by the critics of Omega. With the use of the two VLF frequencies, the ambiguities are about 24 miles apart (10.2 and 13.6 kHz create a 3.4 kHz heterodyne). If the third frequency (11.33 kHz) is used, the ambiguity is reduced to 72 miles, yet with little additional cost. A common multiplier frequency (408 kHz) exists for all three tones permitting simple data processing. The fact is that lane ambiguity of Omega is a problem of equal importance to the LOP ambiguities ("to-from") of VOR; they are quite similar in operational concept, particularly when three or more consecutive VOR's are considered. Neither LF nor VOR ambiguity problems are a serious operational limitation. Certainly no one avoids the use of VOR because of the three to five ambiguities that may be encountered in flying a track that connects a series of radials of VOR stations. Furthermore, the contiguous nature of Omega does not allow a lane to be lost--something never experienced by a VOR-trained pilot who is accustomed to loss of VOR behind mountains and beyond line of sight.

Recall that we are discussing the slow, light, general aviation usage first. We are not discussing or analyzing pilot workload of a 600-knot aircraft, flying on 2,000 to 5,000 mile

trips where the speed and other matters call for a much more sophisticated Omega receiver display and pilot controls than we are reviewing here. Such a study should be conducted; however, its results are more obvious and its impact on ATC trends less. The successful solution to general aviation problems will tend to pace such developments as LF/VLF rather than airline usage, even though the airlines may benefit equally because of their own use of LF/VLF techniques or because the "dispersion" of air traffic routings reduces the traffic densities on routings (say to jetports) of greatest interest to the airlines. VORTAC has been installed mostly for the solution of the latter problem, while general aviation requires an equivalent low-altitude service to thousands of remote airports away from or below jetport terminal traffic. Remember, we are making a one to one comparison of Omega and VOR pilot usage within only a 100 X 100 mile square, as in Figure 14. Of course, the ease of transition to adjacent 100 X 100 mile squares of airspace is equally significant. Even though we use "building blocks" of 100 mile squares in each case; this is done so that the VOR is given equal treatment on a station-by-station basis with Omega or VLF type systems. All the coverage at low altitudes for general aviation that is expected from VOR under favorable siting conditions is utilized. Probably in some locations, a 75-mile square at an altitude of 1,500 feet is more realistic, reducing the low-altitude area by almost 50 percent for VOR. At a diagonal on the 75-mile square VOR the aircraft would still be about 50 miles from the station (see Figure 14).

D. COLLISION AVOIDANCE SYSTEMS AND VLF NAVIGATION COORDINATES

The recent investigations of several collision avoidance systems (CAS) (references 21 and 22) by the Congress of the United States emphasize the confusion that exists on this subject. From some viewpoints there is no such thing as a true collision avoidance system. CAS is probably a misnomer. This popular term emphasizes a desire to avoid collisions but as a technical title of a system it is poorly conceived. We will shortly point out that pilot track following of a universal navigation system superior to

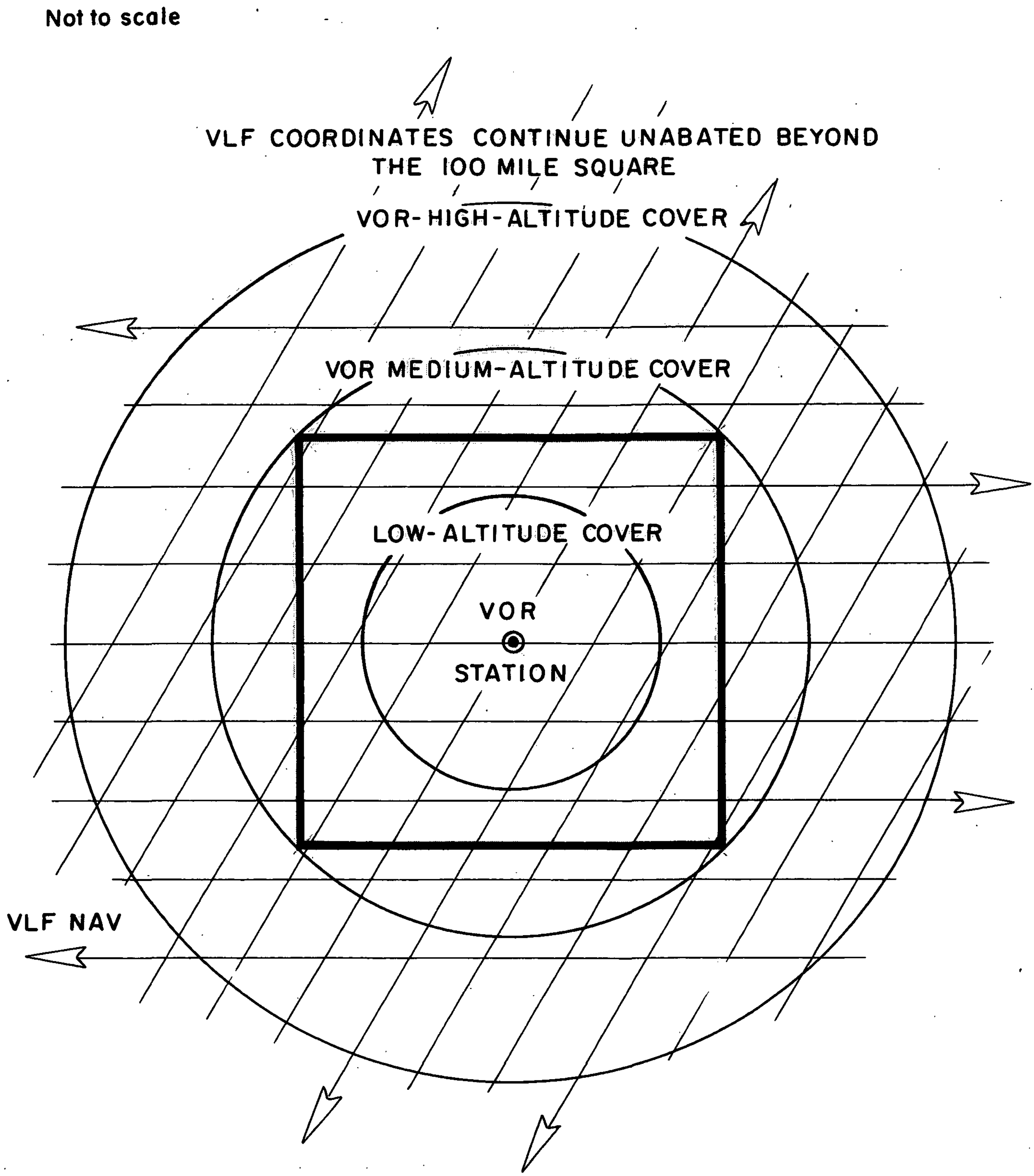


FIGURE 14 A ONE-TO-ONE COMPARISON OF VOR AND VLF/NAV IN AN AREA 100 X 100 MILES

INFLIGHT WORKLOAD FOR A SINGLE GENERAL AVIATION PILOT USING DIFFERENTIAL OMEGA OR VOR

PILOT FUNCTION	VOR(or VORTAC)SYSTEM	LF/VLF"OMEGA-LIKE SYSTEM
1.*Radio Channel Selection	(a)Look up in Chart (b)Turn Knob or Digit Selector	None - 3 fixed channels for all of U.S.
2.*Station Identity	Audio Monitor by Pilot to Assure Correct VOR	None Required as No Erroneous Stations Exist
3.Ambiguity Resolution	Observe "To-From" Indicator	Observe 72-mile Ambiguity Indicator
4.Course Line Selection	Set OBI Selector for each One	Set LOP Selector
5.*"Fixing"on Course Line to Obtain Position	Must add DME or Retune to Another Adjacent VOR and then back to 1st VOR, Creating High Workload	Receiver Continuously Obtains 2 or more Crossings of LOP's Automatically. Low Workload
6.*Course Deviation Flight Following	R-L Meter with 20 to 1 Variation in Sensitivity. High Load on Pilot	R-L Meter with Constant Sensitivity. Thus, Low Pilot Load
7.*Adjacent 100 X 100 Mile Areas	Must Retune and Repeat 6 Steps above for Each Area Adding High Workload on Flights Over 100 miles	Contiguous Coverage, No Retuning. Low Workload
8.Way-Point Selection for "Area-Nav," Parallel Airway, etc.	Set Digit Wheel for Each Way-point and Add Costly 3rd Unit to a VOR & DME which is an R-Nav Computer. Equal Workload	Set Digit Wheel Receiver-Only Creates Simple Coordinates, Voiding Costly R-Θ Computer and DME. Equal Workload
9.*Pilot Assurance Prior to Takeoff	Can Tune to "VOR-Test" Signal into Few Large Airports, Otherwise None about 90% of Time	Full Operational Check While on Runway of at least 2 LOP's Zero Set Indicator to Actual Position
10.*Altitude Effects	a.Curved Course Near Station in R-Nav b.Vertical Nulls in VOR c.Vertical Nulls in DME d.Cone of Silence e.Lack of Useful Signal at Low Altitudes below 700 feet or Behind Mountains	NONE. Works with Nearly Vertical LOP Measurements from Airport Surface to Over 60,000 feet
11.Atmospherics	Minimum	More Susceptible but can be "Engineered" at Low Cost Out of System Usage with Modern Digital Circuitry

* VLF (Omega's) Cockpit Workload Appears Less Than VOR or VORTAC.

VORTAC is one of the best means to assure air-to-air separation. More importantly, assurance of air separation from ground obstacles, such as mountains, power lines, irregular terrain, buildings, etc., will reduce fatalities more than air-to-air techniques. Both are needed to protect each aircraft from collisions with the surface objects or other aircraft. VLF can be used to aid in both cases because of its universal, simple coordinates and low altitude signal coverage. The illusion of some breakthrough solving the air collision problem is prompted by some of the admittedly spectacular mid-air collisions occurring during the past 10 to 20 years since the famous Grand Canyon case. Newspaper and magazine pictures of a broken DC-8 lying in the streets of Brooklyn, the result of a mid-air collision with 100 percent fatalities, will not soon be forgotten.

Scientific and engineering attacks on preventive means for vehicles in motion to avoid collisions has long been sought in both marine and air navigation.

The United States' preoccupation with several sophisticated "CAS" equipments is reviewed by a European expert in a recent journal (reference 23). His views may be more objective as a controversy over techniques has arisen in the United States (references 21 and 28). This authority notes the "scientifically frustrating" situation in aviation that has developed, and he relates them to similar frustrations in the marine world. The following summarizes from this informative paper on air-to-air collisions:

A. No matter how early the threat (air-to-air) is detected, the angle and range data is so limited it is impossible for the pilot to make a successful contribution to avoiding a collision by using information derived from range, relative velocity, and bearing angle.
B. Using range and elevation (and their first derivatives) for a vertical maneuver within the existing ATC limits for vertical separation requires altimeter accuracies well outside the FAA standards (see DOT ATCAC study on accuracies of barometric altimeters, reference 24).

Three-sigma altimeter errors of 620 feet are estimated for general aviation and nearly 300 feet for air transports

(reference 24). Unless a national "in-flight" altimeter calibrating system is developed, assuring no more than about 100-foot errors in terminal area operation, any CAS system requiring less than the 1,000-foot vertical separation must first solve the altimeter error problem. Most such CAS systems "command" the pilot to execute a rapid vertical change of about 200 feet, a value much smaller than DOT/FAA reported errors of altimeters. All altimeters, particularly general aviation, must be considered. For example, two aircraft actually separated (vertically) by 200 feet (within FAA tolerances) might collide as a result of the 200-foot vertical height change commanded by the CAS indicator. In any system engineering involving possible fatalities, the measurement accuracy should exceed the operationally desired results by five to ten times. This would suggest that vertical maneuvers of about 1,000 feet would be commensurate with current altimeters, something completely unacceptable in our national airspace system where the 1,000-foot vertical separation has become standardized.

The following extracts, quoted directly from the author's paper, further clarify this view:

1 "For two aircraft, in straight line flight at constant speed, that are due to miss each other by a small distance m it can be shown that m is given, approximately, by either of the formulae:

$$m = (\ddot{r} r^3 V^{-2})^{1/2} \qquad (1)$$

or

$$m = \theta r^2 V^{-1} \qquad (2)$$

where r, V and θ are respectively the range, relative velocity and relative bearing of the two aircraft. The practical difficulties of basing a collision warning system on either equation are formidable. If M is 1,000 ft., V is 500 ft./sec. (300 knots) and r is 15,000 ft., then $\ddot{r}$ is 0.08 ft./sec.^{2} and θ is about 0.002 radians/sec. The sight line is therefore rotating just a little faster than the minute hand of a watch. Neither a human observer nor a radar scanner is likely to detect such a movement."

2 "...then unless our pilot can detect a sight line rotation of about 1° per second it is impossible for him to make a

useful contribution to avoiding a collision no matter how early the threat is detected."

3 "...time-frequency system which is based on collision avoidance by vertical maneuver in response to telemetered height data from the other aircraft. Broadly, the object is to make a last-minute maneuver to miss the threat by a vertical distance of the order of 200 ft., so that it is possible to argue that ATC rules are not infringed by the maneuver. An attempt is made to guard against the worse-case situation (assumed to be a ½g turn by either aircraft or a rate climb/descent of 10,000 ft./min.). The logic measures relative range and height, and their first derivatives, for all equipped aircraft in line-of-sight, and computes for each the ratio of change to velocity, or 'Tau',..."

4 "Holt and Anderson give some account of the underlying theory, but it must be cautioned that there is a shortage of experimental evidence to justify the numerical assumptions. In particular an altimeter could easily meet the present day FAA standards and fall well outside the limits assumed by Holt and Anderson."

5 "It can be argued that even a moderately effective collision avoidance device used in this way is well worth while; the question is whether the hazards due to avoidance maneuvers in response to false alarms are themselves as dangerous as the situations being avoided. Since at a rough estimate there may well be 1,000 full-scale alarms per collision this possibility is far from remote.

"The fundamental difficulty is that in a crowded terminal area, where the collision risk is greatest, ATC is planning quite intricate traffic patterns. Even the considerable complexity of the CAS logic cannot begin to recognize these patterns and to make a sensible differentiation between 'safe' and 'unsafe' situations. A comparable expenditure on electronics to aid ATC rather than to set up in rivalry might show much better returns."

There is a growing view that the pilot should maintain a track that avoids other aircraft based on a centralized plan affecting all traffic for some time span into the future, say, 30 to 45 minutes or even an hour. This is part of the concept of "Broadcast" or "Strategic" Air Traffic Control. Both VFR and IFR flights are directly or indirectly controlled. Uncontrolled flights, wherein the pilot flies any path he desires are rapidly becoming a thing of the past. A collision avoidance system will do little more than they have done in the marine world unless all traffic moves in some form of specified airspace. For example, nearly all ships have radars of one form or another; however, the marine collision rate has been so bad with radars operating that studies on "radar-assisted" collisions have been undertaken. With much longer marine warning times, there is yet to be found any universally accepted means of marine collision avoidance except by some form of central control, such as shore-based radar and Navaids.

If a uniformly spaced set of universally available coordinates exists, such as LF/VLF coordinates (like Omega), it is likely that the aviation collision avoidance problem would be solved by much simpler means than now proposed in independent CAS systems. The present unavailability of this uniform, low-cost, universally available set of coordinates is probably the basic cause for air collisions. The so-called VFR "see and be seen" concepts of free flight by aircraft must become a thing of the past as aviation expands. Another analogy is roads and highways. Just as roads "organized" surface traffic movements from random cross-field tracks thousands of years ago, a similar "air track" to specific desired destinations at all altitudes must now be provided aviation. Simply put, two motorists approaching each other at high speed on a road cannot avoid each other based on their observations of the angle or range data (or their derivatives) as the values are too small to be useful in time to avoid an auto collision (as the reference above clearly states). The driver of an automobile knows from common traffic rules that he must stay on his lane and be centered on it, thus occupying only half of the

road and, thus, he will avoid collisions with all the other oncoming vehicles.

Lane assignment and use by every participant, conforming to universal rules, requires a common means of forming tracks at low cost for all parties to comply. This is another facet of "Broadcast Control." Aviation must ultimately adopt this concept, but the concept requires a navigation and guidance system that will allow continuous "roads" to be specified by authorities in any direction, anywhere, and at any altitude before the concept can be adopted. Radar surveillance is not the entirety of ATC. Navigation coordinates must come forth that determine all ATC procedures. VORTAC with its many deficiencies of interrupted service, at low altitudes, high pilot workload, and poor "geometrics" consisting of a thousand randomly located, separate, spherical coordinate systems not related in any manner simply won't permit new concepts of Broadcast Control to evolve.

Thus, one view is that to avoid collisions between aircraft, we do not need a new independent CAS system that might result in "radar assisted" collisions, but to go to the heart of the problem and provide universal, simple lanes and assigned air tracks that assure positive separation under all conditions of VFR or IFR and avoiding the "see and be seen" concept (almost completely) in ATC rules.

E. CONCEPTS OF "PROXIMITY CONTROL" OR AIR-TO-AIR SEPARATION TECHNIQUES

The previous discussion is not to suggest that all problems are solved if independent tracks are provided in three dimensions. Just as in rear end and intersection collisions between automobiles, the common track separation criteria must also be established. That is to say, many aircraft will use a common track that may be contiguous (without frequency change) for short or long distances, even up to 3,000 miles across the nation. Such a grid of tracks exist everywhere. The problem identified here is that two aircraft on a common track at different velocities may close the spacing between each other so that separation criteria are violated, simply because the aircraft cannot see or measure

this separation between themselves, or perhaps because centralized ground ATC is lacking for one of several reasons, technical or administrative. The centralized ground ATC, with the three billion dollars of SSR investment, will not change substantially for at least 10 to 20 years. However, SSR (for ground surveillance and ATC) operating at a frequency of 1,000 MHz does suffer from coverage gaps. In dense traffic areas the SSR coverage is extensive, with about 700 stations in the United States alone (and perhaps ultimately that many in Europe).

Thus, two pilots would observe the fact that each is proceeding according to new ATC rules on the same common track, by an air-to-air exchange of data. This air-to-air exchange would also establish the assigned altitude, range, and bearing of the aircraft. Bearing may be used by sophisticated aircraft to pass a slower aircraft on a common track, a concept of something quite different from collision avoidance (as previously described). Pilots will note parallel air tracks (just as in highways sometimes with up to 8 parallel lanes, 4 lanes in each direction). This concept of proximity control then shifts a major ATC load from the ground controller's responsibility to the pilot, where it is more commensurate with pilot responsibility. The pilot is present where the actual controls exist to affect these ATC functions of Proximity Control. The pilot can, without dozens of air-ground complications, follow a track and schedule with high tolerances and view traffic ahead and behind him on his common track. This "fore and aft" pilot-to-pilot control assures the overall requirement that the ATC separation criteria (say spacing is of two to three miles) is not violated. SSR will overview the separation but not control it.

Several existing systems or techniques will permit this air-to-air exchange, the most likely being the airborne SSR transponder, since (1) it already exists, (2) it sends out altitude and identity codes automatically and continuously, and (3) it can be readily received by other aircraft with the addition of a receiver and a simple processor. The aircraft using its SSR transponder can now send over 4,000 codes for ATC purposes. Such codes are now assured, but others are available or assignable without any change in the national standard for this three billion dollar system.

F. ATC EXTRAPOLATION OF SSR AND LF/VLF SIGNALS FOR ATC PURPOSES

It can be argued that at low altitudes, such as the 400-foot decision altitude (DA) of a non-precision approach, that ground ATC (SSR) surveillance cannot be assured across the nation. This is to say that LF/VLF, not being restricted by line-of-sight radio transmission, can now be used to create a three-dimensional approach track to any runway or strip in the nation. With differential LF/VLF data acquired simultaneously with barometric data, it is possible to obtain by existing communications simple "canned-voice" messages from a Unicom frequency with an identity acknowledgment to the requester. A simple technique is suggested in Figure 15 using standardized elements of our national telephone network. This low density, remote area general aviation concept could offer adequate service to general aviation at a cost level to meet their needs.

With the new concepts of ATC, where the airlines may stay above 4,000 to 5,000 feet until near the terminal, general aviation may use altitudes between the lower of these "keep them high" altitudes and the minimum altitudes typically of about 1,500 feet. Thus, we have some segregation of traffic. However, climb corridors must be crossed occasionally and some of these are as long as 35 miles, extending from the jetport to a height of about 14,000 feet. A pilot flying VFR must call ATC to cross these corridors. This type of operation and many others effectively require some form of SSR surveillance which is only available above about 1,500 feet on a national basis. Considerably less SSR coverage than this exists at, say, 400 feet. Typically, about 50 NM range to 200 NM range is possible with well sited SSR stations interrogating aircraft above 2,000 feet. Coverage decreases to about 20 NM at around 700 feet and about 10 NM at 300 feet. Although the above values are only approximated, varying in value according to topography and elevation of the SSR interrogator, from the viewpoint of general aviation the values are of great significance.

If, for example, a general aviation aircraft operating at 3,000 feet is being tracked [while it flies on an LF/VLF (R-Nav) airway] by SSR ground surveillance, and then starts to descend in

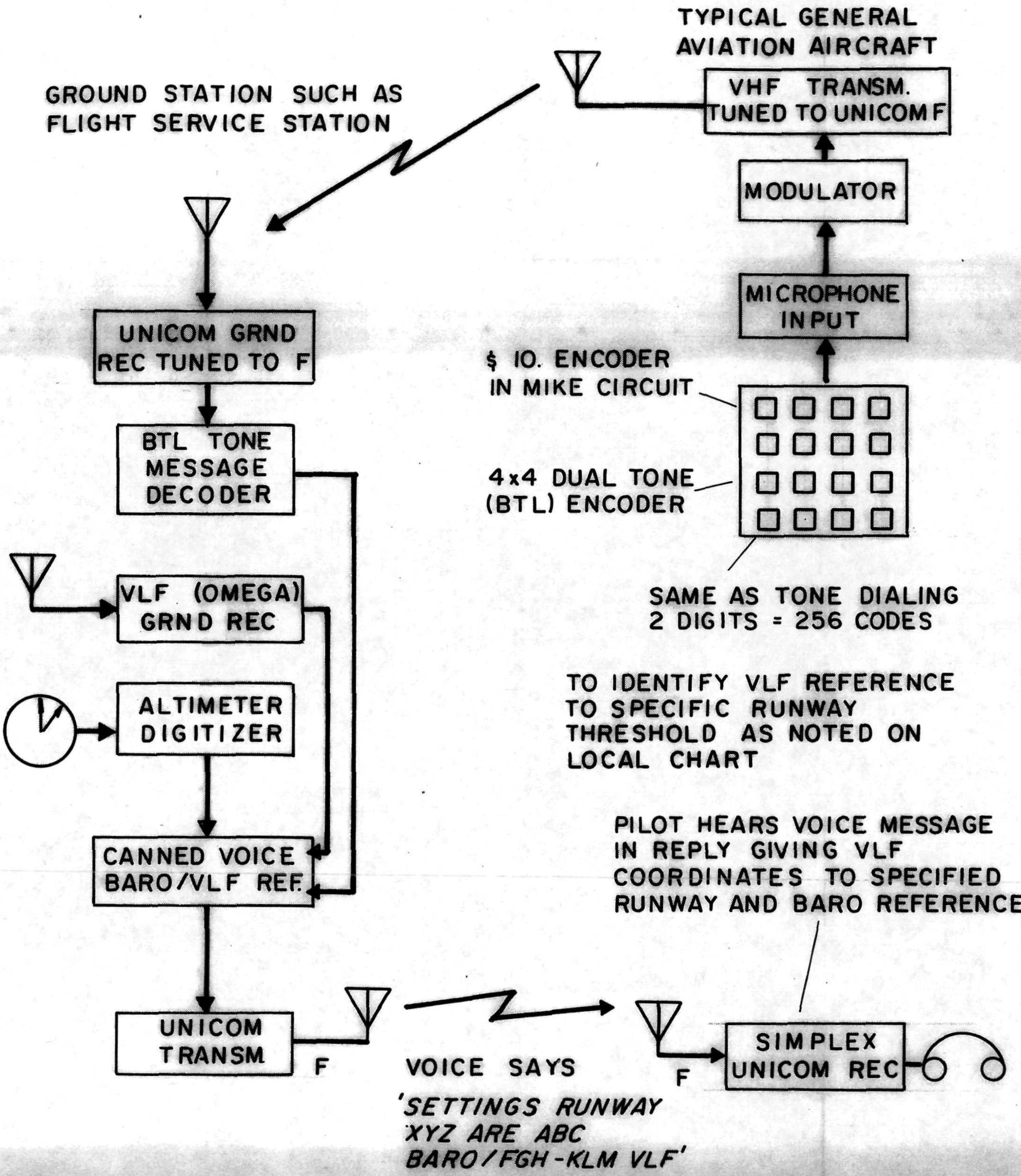


FIGURE 15 ADDITION OF $10 TONE ENCODER TO EXISTSING AIRCRAFT VHF COMM UNITS PROVIDES SELECTIVE DIFFERENTIAL OMEGA (VLF) DATA AND BAROMETRIC SETTINGS

altitude, going below the coverage of the national SSR network in that locality; the path, track and schedule can still be accurately extrapolated by ATC. Since both SSR and LF/VLF are in use prior to the time of descent, either can be used--VLF of course being preferable.

When the pilot is allowed, say, to cross an airway or corridor or to let down into a remote airstrip beyond SSR cover, the combined SSR and LF/VLF tracks prior to the loss of ATC centralized ground tracking are used by the controller to extrapolate the next section of the flight that follows an agreed-upon track, altitude, and time profile. Using this procedure the pilot is assured that the R-Nav data is registered by and with the independent measurements of the SSR; the pilot is assured that track speed, wind, heading, etc., have been computed prior to leaving SSR cover and entering extrapolated ATC procedures on LF/VLF coverage. Since the VLF coverage may permit a non-precision approach into a remote airport without a control tower, the SSR ATC data can be used to assure the pilot that the extrapolated low-altitude track is correctly aligned with runway centerline (angle and displacement) and that the altitude descent schedule will be executed with minimum risk. This is the "differential Omega" concept introduced as an integral part of ATC, so that all errors are independently checked prior to exposure to obstructions on descent. Non-conflicting airspace, available for another flight, is reduced in this manner.

Since the three-dimensional R-Nav position is shown to both pilot and controller alike (video-map displays for the controller and R-Nav cockpit displays for the pilot), the two systems can be brought into registry. Since LF/VLF is a contiguous system of coordinates, it can span many SSR systems connecting any two SSR surveillance systems together where overlapping coverage is not possible by a simple pilot dead-reckoning when between the two coverage diagrams. It is not always possible, economically or technically, to achieve SSR surveillance, say, to altitudes below about 500 feet surrounding remote airports. Thus, traffic at about this altitude or lower will go into and out of SSR coverage as seen in Figure 16. If the aircraft were at higher altitudes,

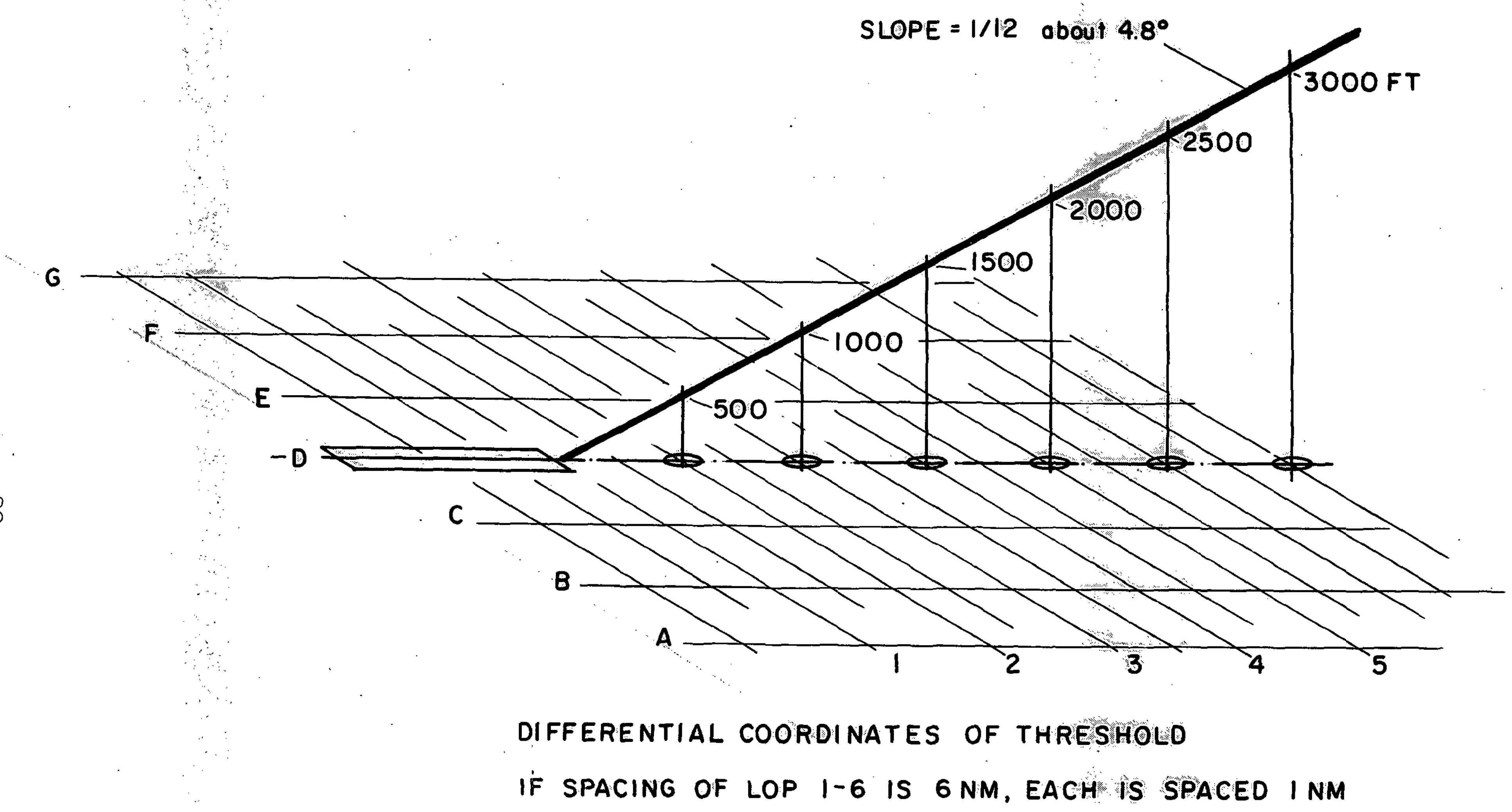


FIGURE 16 PROGRAM OF ALTITUDES FOR NON-PRECISION APPROACH TO A RUNWAY USING AN "OMEGA-LIKE" NAVIGATION SYSTEM

the SSR cover is greatly improved, but the general aviation aircraft then may be forced to "mix" with the higher speed jets and be possibly affected by wake turbulence, delays, collision threats, etc. VORTAC coverage is not continuous nor is SSR coverage continuous, so that the two do not complement each other very well for this concept of ATC extrapolation. In fact, the low-altitude coverage of SSR and VORTAC is not even coincident, since the two polar coordinate systems (both line-of-sight limited) are not sited at common locations (except in a few rare instances). However, with contiguous coverage at all altitudes of VLF/LF systems, such as Omega, this coordinating or integrating together the coverages of adjacent SSR sites is readily possible and should be a great asset to ATC.

A controller, knowing the aircraft is going into a location beyond SSR range, can extrapolate and "hand over" the traffic to another radar and controller while the pilot continues on the same grid uninterrupted since the same grid overlays both SSR sites and all other SSR sites. The controller can also, in emergency conditions, give the pilot his LF/VLF coordinates by correlating the SSR data with LF/VLF coordinate data, something easily done with the hundreds of digital processors in operation that convert R-θ SSR data to rectilinear data, since the overlay will permit this. That is to say, the differential corrections of LF/VLF can be provided by the controller and his SSR processor since the two systems' accuracy is about equal on average on a 100 X 100 mile basis. Thus, pilot use of LF/VLF systems for Broadcast Control is differentially corrected routinely (once an hour) by the total system, minimizing the need for localized corrections. For example, the pilot might switch to one of the 4,000 identity codes reserved for transponders and obtain his differential Omega data automatically addressed to him in a "canned voice" communication, similar to what is shown in Figure 15.

G. "VFR-AIRWAYS" USING LF/VLF

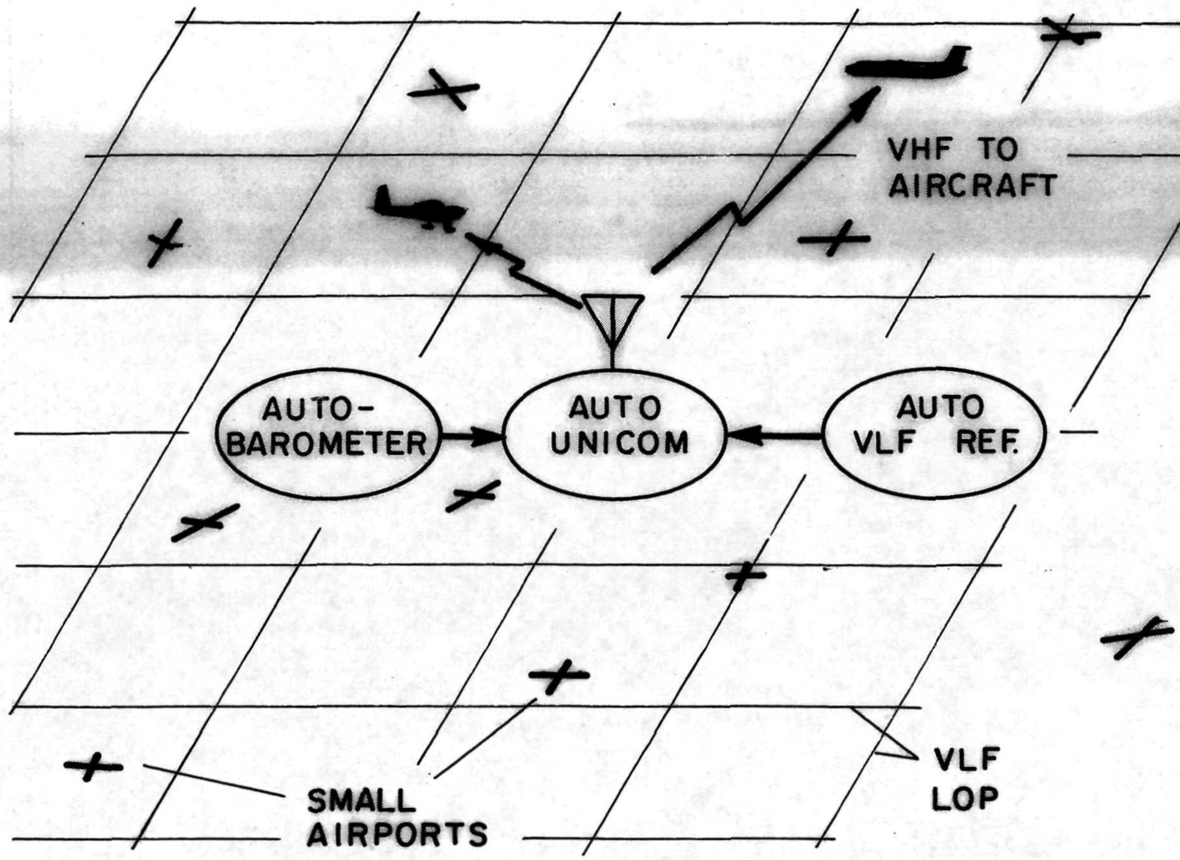
Some proposals for introducing the LF/VLF system concepts of ATC are based on the "controlled" airspace being established by

VORTAC coordinates and the VFR's airways for general aviation being LF/VLF systems. The latter create airways parallel to but separated from the controlled airways (reference 26). This concept effectively suggests that simple "see and be seen" VFR navigation is becoming a thing of the past. This concept, suggested as a possibility by the FAA (reference 26) offers a first evolutionary step that may be acceptable to many private and government authorities, so that a real test of VLF/LF can be realized. In this manner, general aviation would not be required to follow the dense airline airways. The user of the smaller aircraft could be assured of ATC protected, non-conflicting flight paths with respect to the airlines, and the airlines can be assured of ATC protected, non-conflicting flights with respect to small, single-pilot, single-engine aircraft. Most importantly, this concept provides signal coverage and ATC service otherwise not available to general aviation, encourages "dispersion" of traffic rather than "convergence" of traffic, and typifies the principles of Broadcast Control. Figure 17 illustrates this. This VFR airway plan could be a three-dimensional concept where the two LOP's horizontal dimensions are created as well as vertical dimensions. The simplicity of pilot VLF usage over VOR usage and the contiguous low altitude cover of VLF, previously described, suggests that with perhaps a 10-percent increase in instructional times, a private pilot could be capable of at least avoiding specified areas, and perhaps could even fly a "VFR-airway" at the time he receives his pilot's license.

H. NOISE ABATEMENT USE OF LF/VLF NAVIGATION (VSTOL AND GENERAL AVIATION)

As noted previously, the average (area-wide) accuracy of an "Omega-like" VLF system is superior to VORTAC and with differential corrections can be provided the pilot approaches that are on runway centerline, avoiding approaches with up to 30 degrees of divergence and avoiding positional errors from remote off-airport VORTAC's. Or conversely, one can argue VLF will avoid the addition of about one to two thousand more VOR and VORTAC's to give a 400 and one mile service to all of the thousands of general aviation

VLF COORDINATES IN AREA ABOUT 50 x 50 MILES



AUTOMATIC UNICOM PROVIDES BAROMETRIC AND VLF REFERENCE DATA TO EACH AIRPORT IN LOCAL AREA SO THAT ONE VLF GROUND RECEIVER SERVES AS MANY AS TEN AIRPORTS IN AREA

FIGURE 17 AREA USE OF DIFFERENTIAL OMEGA REFERENCE DATA GREATLY REDUCES COST OF VLF USAGE

airports that now need such service and allow for expansion of new airports based on the approval of a VLF non-precision approach.

In many cases these small airports are readily located in or near residential communities where noise from even light, single-engine aircraft must be considered an annoyance because of the generally low ambient noise level. Furthermore, if STOL or VSTOL is to be taken to "where the public is" at many locations away from the major airports (many experts feel both aspects are essential to STOL or VSTOL's technical success and public acceptance), then a means for configuring noise abatement approaches to all runways at all airports must be considered. A generalized solution applicable to any and all cases must be sought and not a "customized" noise abatement procedure for each runway and each community that involves special electronic aids, such as localized ILS, VOR, VORTAC, etc., as these aids are far too costly for each airport to cover, for example, the four approaches to a cross-wind STOLport.

Typical steep-angle approaches are in the range of about 4 degrees to about 14 degrees for STOL, general aviation, and helicopter aircraft. The following table gives various ratios of height vs distance in ratios such as 1:5, 1:10, 1:15, etc., and the corresponding glide path angle to the nearest tenth degree.

GLIDE SLOPE	DEGREES	GLIDE SLOPE	DEGREES	GLIDE SLOPE	DEGREES
1 : 22	2.6	1 : 16	3.6	1 : 10	5.7
1 : 20	2.9	1 : 15	3.8	1 : 9	6.3
1 : 19	3.0	1 : 14	4.1	1 : 8	7.1
1 : 18	3.2	1 : 13	4.4	1 : 7	8.1
1 : 17	3.4	1 : 12	4.8	1 : 6	9.4
		1 : 11	5.2	1 : 5	11.1
				1 : 4	14.0

The above table has the convenience that one can easily relate the height of the aircraft along the descent path using simple fractions. For example, on a 1:7 path or about an 8.1-degree path, the aircraft is 1 NM high when 7 NM from the threshold. When the aircraft has then descended to a height of, say, 1,000 feet, then the aircraft is 7,000 feet from the threshold, and finally, when at, say, a 400/1 DA (decision altitude) condition, the aircraft is

7 X 400 or 2,800 feet from threshold. Furthermore, when examining the piloting aspects of steep angle approaches, past experience shows that much "selling" or convincing of pilots on the real merits and risks is essential. One matter of concern to pilots is the complexity of mentally computing angles, distances, heights, etc. A simple instrument as the one illustrated in Figure 18 would suffice as the table would be an adjustment the pilot makes when he selects the steepness of the angle. He does this based on his own ability, skills and the prevailing noise abatement requirements. This simplified, low-cost display illustrates the direct "raw" type data that can be utilized by the pilot of a slow aircraft, typical of general aviation. The pilot compares the barometric altimeter reading at 4 or 5 points while on the approach according to the location of the VLF "distance-to-go" needle. These are admittedly old instrumentation techniques; one radio altimeter indicator has a scale that changes for different ranges that could be easily modified for such a display. Similarly, several DME indicators use meter movements that do the same thing.

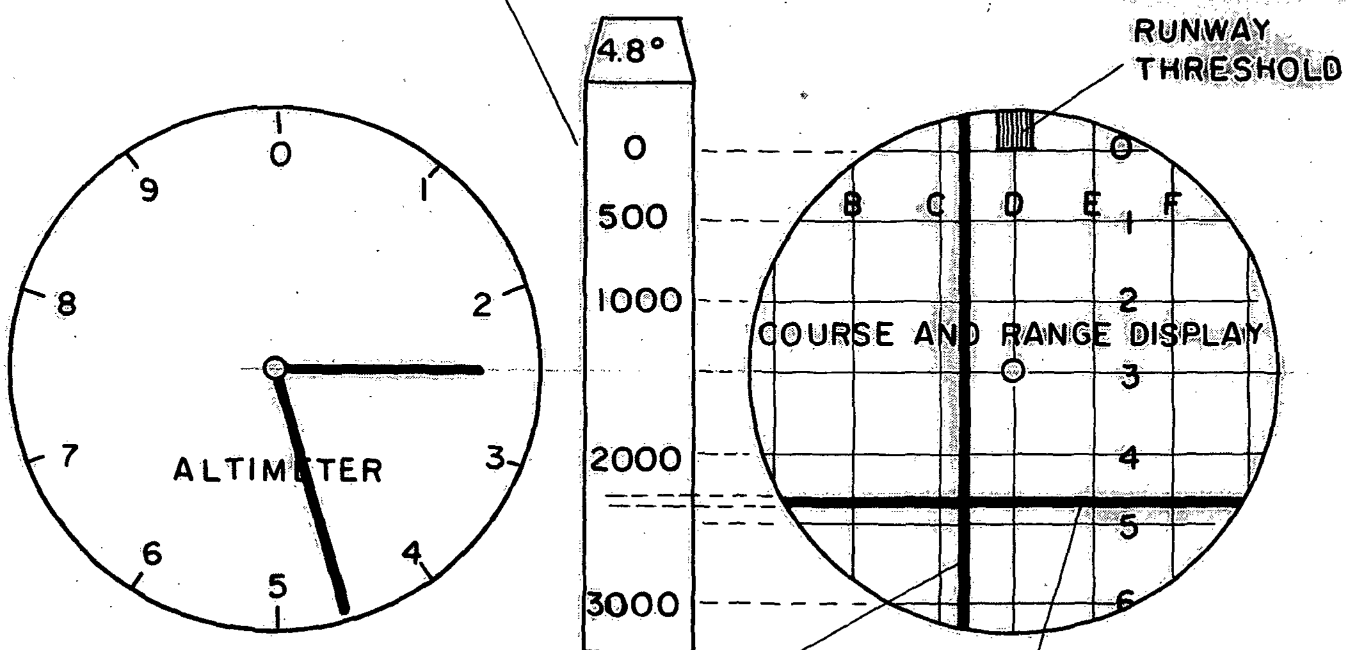
Thus, a small airport in its agreement with authorities to keep noise down and to prevent flying low over adjacent houses would operate perhaps at some angle typical, say, of a light aircraft of about 7 to 8 degrees. The important point is that this would be consistently adhered to at all times and, furthermore, would "visually train" the pilot who has only limited IFR experience so that each time he flew on this type of steep angle display, he could judge his own ability. When he is IFR, flying non-visually to a decision altitude (DA) of, say, 400 feet, his first sight of the ground will not be a shock and he can be aware of the new visual cues to be expected.

I. MULTIPLE VS SINGLE SEGMENT NOISE ABATEMENT APPROACH

The simple, single segment approach for general aviation ATC not only will prevent pilot errors in longitudinally estimating a track to the runway (such as localizer-"only" or VOR-leg "only"), but could be used in community noise control programs to assure the community that certain angles were being adhered to. This method of communicating with the opponents of aviation should prove

THIS SCALE BETWEEN THE ALTITUDE AND COURSE AND RANGE DISPLAYS IS USED TO "CUE" THE PILOT OF HIS ALTITUDE FOR THE CHOSEN GLIDE PATH (1/12=4.8 DEGREES).
TYPICALLY THE PILOT IS AT ABOUT 2500 FEET.
HE IS SLIGHTLY TO THE RIGHT OF THE EXTENDED CENTERLINE.
HE IS ABOUT 5 MILES FROM THRESHOLD.

BY TURNING THE KNOB OF THE SCALE, OTHER ANGLES ARE REPRESENTED (4.8 IS SHOWN).



THIS HORIZONTAL NEEDLE MOVES VERTICALLY SHOWING CHANGE IN DISTANCE TO THE THRESHOLD OF FIGURE 19. IT IS POSITIONED BY THE AIRCRAFT'S RELATIONSHIP WITH LOP'S L THROUGH 6. A DME TYPE INDICATION

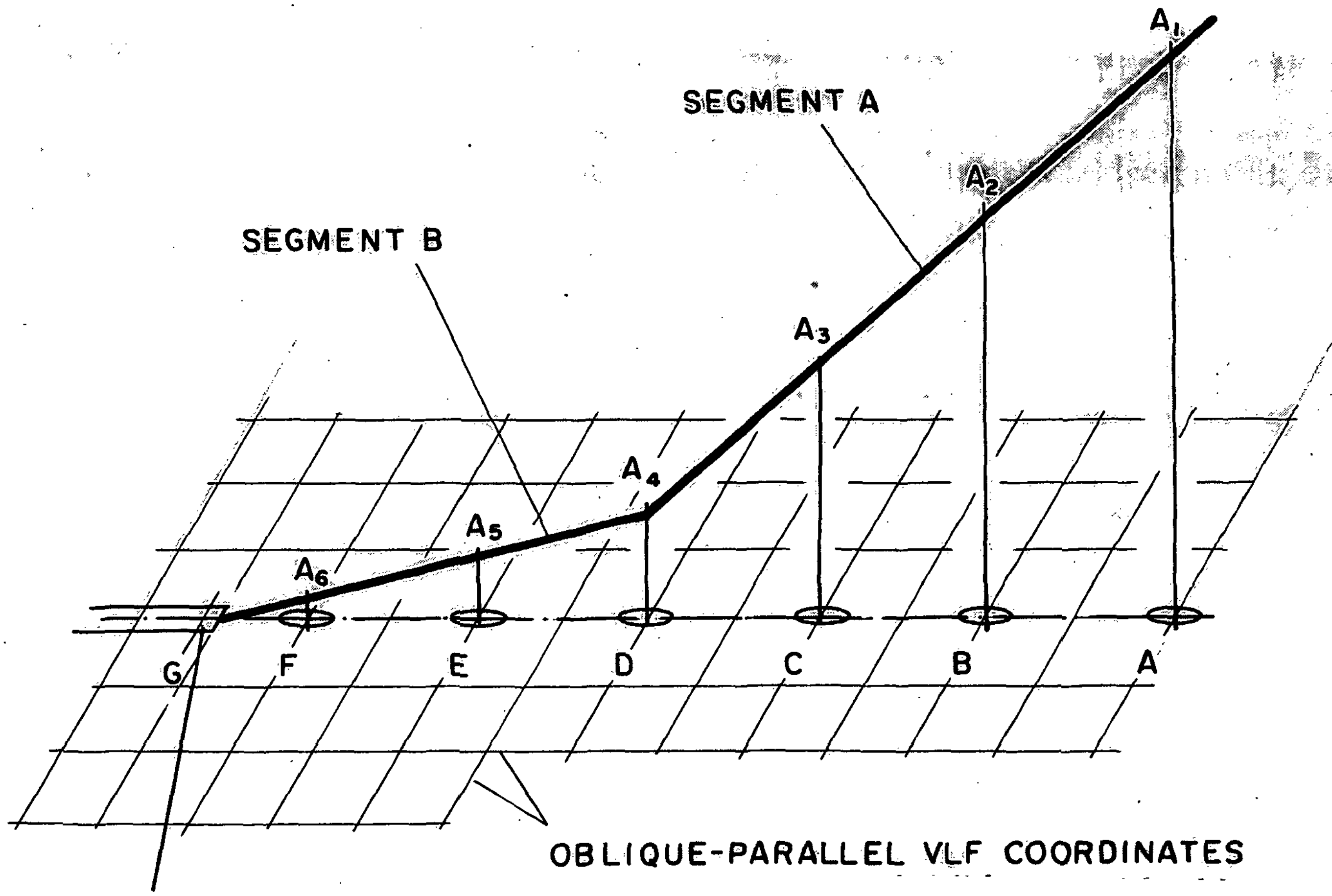
THIS VERTICAL NEEDLE MOVES RIGHT AND LEFT ACTIVATED BY THE AIRCRAFT POSITION RELATIVE TO LOP'S SUCH AS B, C, D, E, ETC.
IT RETAINS A MUTUALLY PERPENDICULAR RELATIONSHIP WITH THE HORIZONTAL NEEDLE

FIGURE 18 LOW COST PILOT INSTRUMENTATION FOR NON-PRECISION APPROACHES USING VLF NAVIGATION COORDINATES

helpful. Each of four approaches to a cross-wind runway airport could have a separate angle, dictated by the location of houses, obstructions, etc.; the point being that the lower angles are used on one or two approaches, and higher angles are used on the others, thus giving flexibility.

In the cases of STOL aircraft, we will expect larger aircraft initially, probably between the size of the McDonnell Douglas 108 (French/Breguit STOL) and the DeHaviland Twin-Otter. The noise levels here and particularly in any jet type (non-prop) STOL will require segmented approaches to (1) reduce noise considerably on the one hand, and (2) yet give the pilot of this larger aircraft a shallower angle near touchdown. Typically, segmented approaches might be a 7-degree path into a 3-degree path, the transition taking place above an altitude of 500 or 700 feet to assure that the lower sink rate is reached well before any 200 or 300 foot altitude limit is reached. In this case the LF coordinates must be displayed with a modified scale for the STOL pilot. Here we deal with a more sophisticated pilot with IFR training and experience. More instrument cues will be needed as well as more sophisticated flight instruments, perhaps even including a curved azimuthal approach prior to the segmented descent. Figure 19 illustrates a "segmented" noise abatement, VLF approach.

If STOL aircraft are to serve many small airports and draw the traffic from the major jetports, thus alleviating the many bottlenecks there, it is essential that this type of approach be possible to perhaps 400-1 NM or 300-¾ NM wherever STOL is needed without a separate ILS installation at each site. Most STOL service to be of public value must be able to operate in cross-winds, so that four approaches must be considered for regularity and safety of public service. Again, a wide-area navigation system, such as LF/VLF, can provide this capacity to the STOL service at low cost. All (4) approaches can be provided with segmented noise abatement guidance for perhaps 10 percent of the national cost of any other "400-1" solution to segmented approaches. When, say, 100-¼ visibility operation is justified (after traffic and public demand builds up for STOL), a separate costly ILS for one or two approaches is then justifiable. Differential LF/VLF, with a



DIFFERENTIAL REFERENCE POINT JUST INSIDE RUNWAY THRESHOLD
LOP'S A THROUGH G ARE ON CENTERLINE LOP OF VLF SYSTEM (COMPUTED)

SPACE POSITION OF SEGMENT A DETERMINED BY COORDINATES OF ALTITUDE AND LOP ($A-A_1$; $B-A_2$; $C-A_3$; ETC.)

SPACE POSITION OF SEGMENT B DETERMINED BY COORDINATES OF ALTITUDE AND LOP ($D-A_4$; $E-A_5$; $F-A_6$ AND $G-A_7$-TOUCHDOWN

FIGURE 19 SEGMENTED STEEP ANGLE APPROACH FOR NOISE ABATEMENT USING VLF COORDINATES

steady-state runway alignment and constant speed approach, should give about 1,000 to 2,000 feet dispersion at the 400-foot decision altitude (DA), something equal to or better than a VOR approach or even an Area-Nav (VOR-DME computer) approach where the average distance to the nearest VOR is considered (up to about 6 or 7 miles).

J. SEGMENTED STOL APPROACHES USING DUAL GPIP's AND LF/VLF COORDINATES

To finally specify a segmented approach in a quantitative manner using LF/VLF guidance coordinates (like Omega), it is best to consider two glide paths, each with a Glide Path Intercept Point (GPIP). This concept is illustrated in Figures 20 and 21. Depending upon the flight characteristics of the specific aircraft, steepness of angle, height over community, etc., glide path angle No. 1 is selected, as is its GPIP. This is the initial steep angle that, through the combination of added height and lower power settings, can provide from 12 to 18 db noise reduction, according to some experts. From several flight research programs at NASA, it has been learned where the steep path (say 6 degrees) should intersect the shallow path (No. 2) in height and distance from the touchdown. This data applies only to the specific aircraft tested, and its applicability to a widely divergent spectrum of aircraft is unknown.

This is likely to vary considerably for different types of air vehicles; however, since we are independent of actual electronic units sited on the ground at specific points, such as GPIP No. 1 and GPIP No. 2 (Figure 21), we are free to configure anything desired in the way of the geometrics of segmented approaches.

We can program into each type of aircraft its best GPIP-angle data. Perhaps four or five "canned" approaches would be available to the pilot by push-button selection, any one program being suitable to his specific aircraft. Where the obstructions, noise abatement needs, might dictate, say, an 8-degree angle for vertical path No. 1 and a 4-degree angle for vertical path No. 2, this as a choice for that approach to that specific runway; a subsequent, less demanding location may allow, say, a 5-degree path transitioning into a 3-degree path for the next specific approach

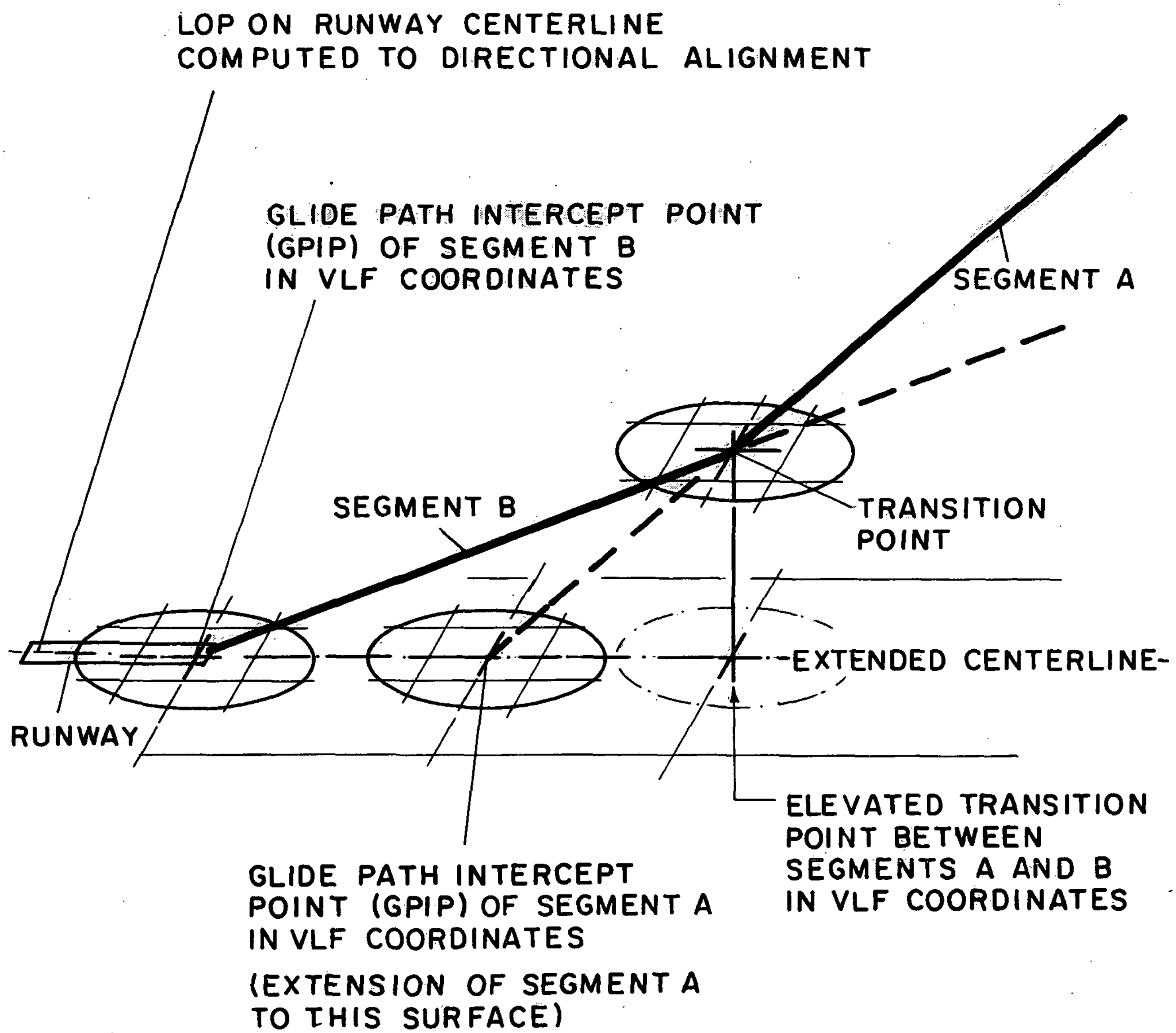


FIGURE 20 USE OF GPIP AND ELEVATED TRANSITION POINT IN "CONSTRUCTION" OF A VLF SEGMENTED APPROACH PROCEDURE

GLIDE PATH INTERCEPT POINT (GPIP)

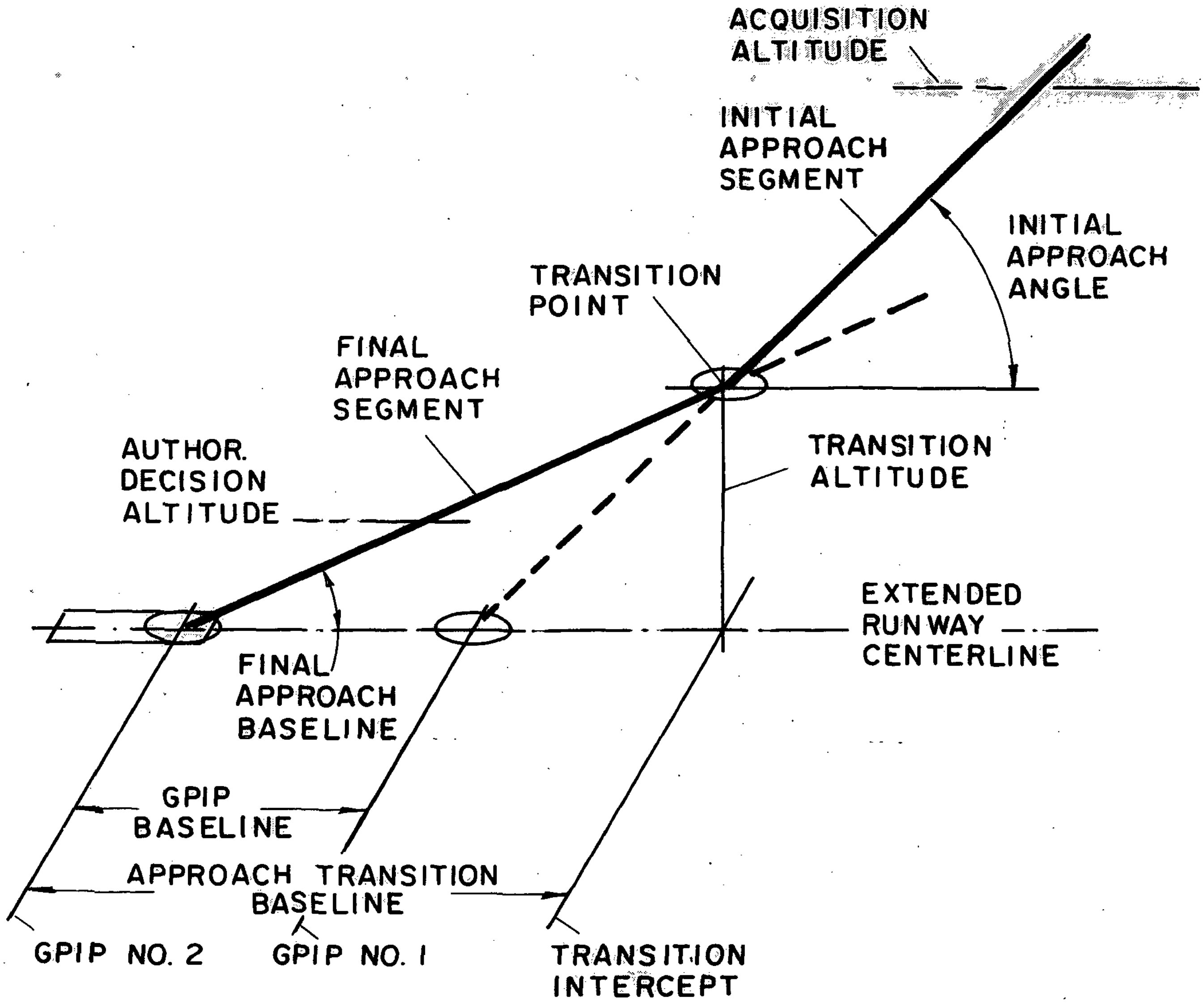


FIGURE 21 DEFINITION OF TERMS USED IN SEGMENTED APPROACHES

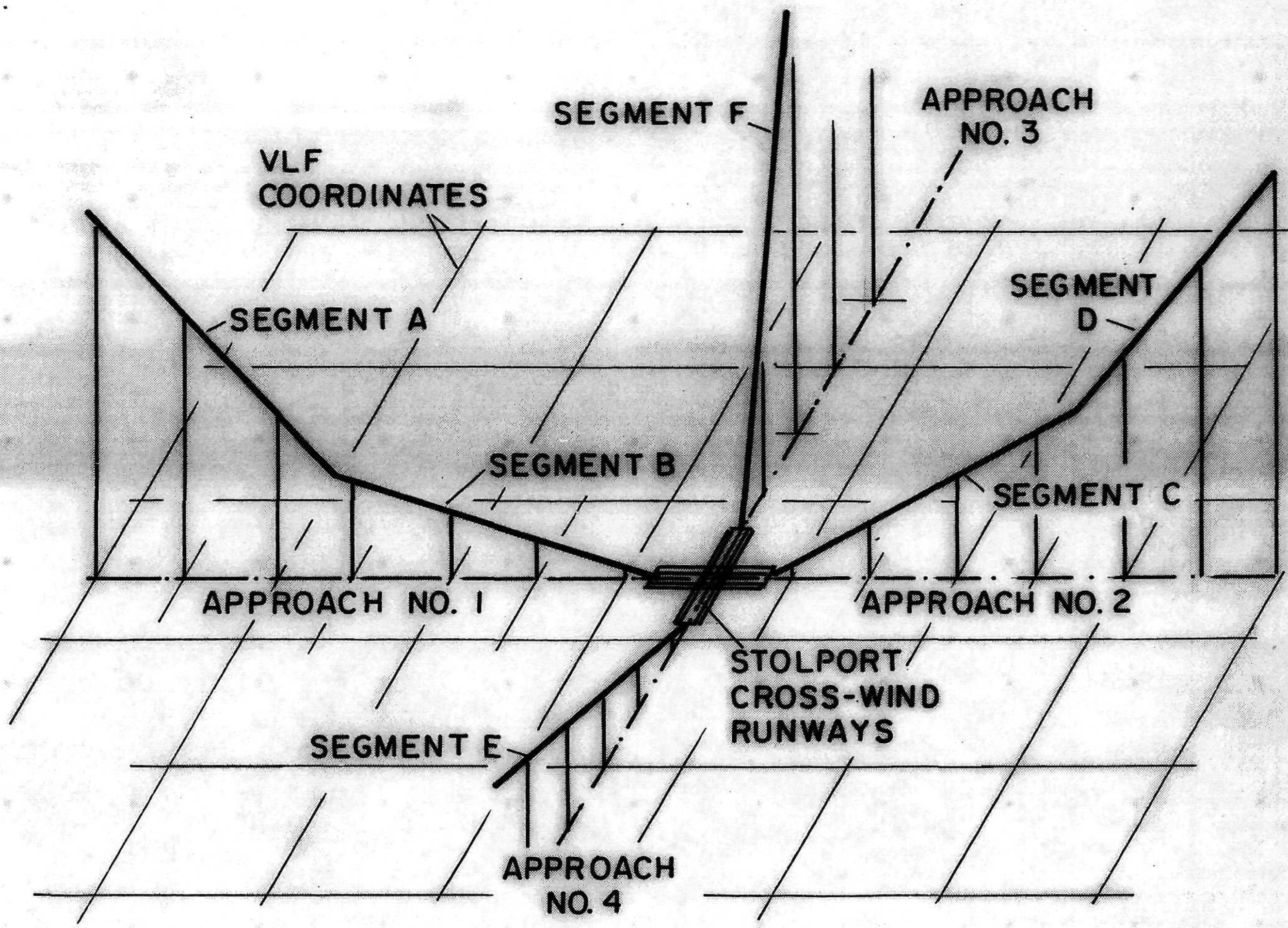
to a specific runway. The optimum four or five of such combinations would be pre-programmed and immediately available to the STOL pilot.

In the programming, the steep angle must be referenced to GPIP (No. 1), and the shallow angle must be referenced to (originating from) GPIP No. 2 (Figure 21). In essence, two glide paths are considered separately in the selection of angle and GPIP origins; all coordinates are in terms of the two LOP's of the differential LF/VLF coordinates and altitude. However, the two vertical paths have an "intercept-point" in space that is also defined three-dimensionally in LF/VLF coordinates (Figure 20). Since the surface VLF signals are the same as signals vertically above them, the VLF coordinates can be each established with a given altitude reference in the segmented approach concept.

Figure 21 defines some proposed terminology for the segmented approach. Although there may appear to be an infinite variety of combinations of the two angles, three longitudinal points, altitudes, etc., a specific aircraft will probably find a range of combinations suitable for most of its many landing environment factors (noise, obstacles, runway length, power, speed, displays, etc.).

However, taken as a whole national program for noise abatement, variations in aircraft types, approach speeds, noise criteria, etc., all possible combinations must be considered to accommodate the piloting and community objectives in each application of the segmented approach. Thus, one type of aircraft might be limited to three choices of segmented approaches; however, another aircraft, because of its differing flight characteristics, might have three different choices, yet each set of three approaches (six total) combines to meet the pilot-regulatory objectives. This flexibility of VLF is shown in Figure 22.

Again it is emphasized that if the community, FAA, and DOD can afford a "customized" steep-angle, segmented approach system for a runway, probably a microwave system derived from the national MLS program, then much lower ceilings could be authorized than "400 and one mile" or "300-¾." However, because of the cost and technical limitations of current VHF-ILS, this system may not be widely applicable to noise abatement in the interim, nor would VHF-ILS be applied except to the most significant locations.



VLF COORDINATES PERMIT APPROACHES TO ALL RUNWAYS TO BE ADAPTED TO THE CRITERIA FOR EACH APPROACH.
FOR EXAMPLE, APPROACH SEGMENTS A THROUGH E MAY DIFFER IN ANGLE, GPIP, HEIGHT ABOVE OBSTRUCTIONS, AND TO FIT COMMUNITY NOISE ABATEMENT PROCEDURES.

FIGURE 22 VHF COORDINATES PERMIT FLEXIBLE SEGMENTED APPROACHES TO ALL RUNWAYS OF AN AIRPORT

The VLF/LF segmented approach is a technical possibility that should be quickly examined and tested as the availability of VLF/LF signals at all STOLports and all general aviation airports is likely to occur well before the more sophisticated microwave landing system is extensively implemented. Omega will be fully operational in 1975, offering this universal service. MLS will be operational about 1980, with respect to widespread STOL installations even though limited installations may occur as early as 1977. In the future the two (VLF-Microwave) can be complementary; one providing, say, "CAT II" landing capacity to STOL service, and the other (VLF) a "400-1" or "300-¾" capacity to STOL. A given STOL route structure that may emphasize high density and low density areas (a typical operational goal of STOL) can readily use the combination of the two.

VII. WIDE RANGE OF BROADCAST CONTROL CONCEPTS

With the introduction of LF/VLF systems, such as Omega and Loran-C, new geometric navigational coordinates will exist that offer many options to the planners of systems for "Broadcast" control of air traffic. In the simplest case, the several lines of position (LOP's of station combinations) create overlapping parallel-oblique lines that often approximate a rectilinear coordinate system. With simple coordinate conversion of these simple LOP's, new coordinates can be created for airways or to form a flight track between any two points.

This VLF airway is then displayed to the pilot with nearly any direction and sensitivity desired since VLF coordinates are universal and contiguous across the nation. Several developments are underway for a "pure" VLF type system that can be utilized by general aviation. We can utilize new airspace for airways not now available, yet suited to the unique requirements of general aviation. Less conflict between general aviation and the airlines and airports and airways is expected as one important product of this plan.

It is possible to postulate a dual system of airways that would essentially (1) utilize VORTAC for providing R-Nav airways to the airliner and jet aircraft operations, and (2) parallel (VLF-Omega) R-Nav airways to the side and at lower altitudes for general aviation's slow, light aircraft.

The problem has always been the electronic definition of airspace suitable for air traffic control. The national constraints of using only the VORTAC system for R-Nav is that only a fraction of the airspace suitable for airways and ATC can be used because of the current "radial-only" concepts of using VORTAC. To state this in different words: a great deal of useful airspace exists that cannot be used today since the method of defining or assigning airspace by ATC authority to aircraft is too antiquated. No estimate has been made on a national basis, but it is likely that, if all the airspace that would be of value to air traffic of 1980 to 1990 were identified, perhaps less than half of it can be adequately authorized for use in ATC concepts since the limitations

of radial-only exist. The locations of the VORTAC stations, convergence of tracks, or line-of-sight propagation limitations, prevent expanded VOR use.

We could probably double the nation's airspace useful to ATC and for airways and airport approaches with adequate coordinates by adopting a new VLF electronic Navigation system. Broadcast control concepts of air traffic control would then be easily instituted with major savings.

Shortly, the national cost to move in this direction will become insignificant when compared with the large benefits. Much of the demand for some form of traffic control suitable for this large, unused volume of airspace must be satisfied. The user's cost for deriving benefits from this newly created airspace must be very low to accommodate general aviation's nearly 100,000 small aircraft.

A recent national conference on R-Nav indicates VORTAC Area-Nav costs cannot be reduced adequately to attract the lower 85 percent economic strata of general aviation (references 30, 31, and 32).

In addition to a supplemental ATC system for general aviation and Broadcast control, which is only an LF/VLF system, it is also possible to postulate a means of interfacing and combining the current VOR system with the current VLF system (Omega is fully operational in 1974).

A. VOR AND VLF NAVIGATION INTEGRATED FOR ATC AND AIRWAYS

We will assume that the nearly 1,000 VOR stations that now exist will remain. The most prevalent avionics unit in an aircraft today, aside from VHF-COM, is the VOR NAV receiver; thus, we can build our concepts on a large installed fleet of VOR receivers in general aviation aircraft. These VHF receivers have been brought down in price so that cost is no longer a constraint to VOR usage. This, however, is not true when DME is added along with a costly R-Nav computer and its display.

The cost of a VOR receiver is now in the $500 to $1,000 range, but the added elements to achieve Area-Nav (DME, computer, displays) are still in the price range from $6,000 to $15,000,

depending upon the extent of computing desired. If altitude correction and three-dimensional navigation are essential, as it now appears (references 30, 31, and 32), the cost then can range above $15,000 for the lowest cost "package" for R-Nav with VORTAC. Defining airways based on many randomly located spherical coordinates is costly and can only be justified by high performance of jet aircraft, thus denying this service to others, since airspace once assigned to R-Nav airways can only be used by aircraft so equipped.

The concepts presented here are intended to overcome this national dilemma which is now clearly in focus from a review of the recent national conference on R-Nav (January 1972). Basically, the idea is to use (1) the VOR with its known strengths and weaknesses, (2) a system like Omega with its known strengths and weaknesses, and (3) VOR and Omega in newly combined and harmonious relationship. In this combination the strengths of one system overcome the weaknesses of the other system.

Table I summarizes some of the methods of overcoming the weaknesses of one system with the strengths of the other system. For example, the very existence of about 1,000 VOR stations, each with a voice channel to the pilot, makes it possible to locally add simple "differential" VLF correction data that can manually or automatically correct the VLF receiver. This directly solves one of the most vexing VLF problems: the "diurnal correction." Another example suggested by Table I is the use of the naturally parallel LOP's of Omega to overcome the converging LOP's of VOR causing airway convergence to a central point which inhibits traffic flow and overloads ATC. Opening up the total national airspace with non-converging airways avoids these constraints and makes ATC much simpler, providing airways in about twice the amount of airspace than is now possible.

B. PROVIDING ENORMOUS NEW AIRWAY CAPACITIES FOR GENERAL AVIATION AND V/STOL

It can be seen in Table I that these many complementary aspects come from a "mix" of VHF techniques and VLF techniques, from two systems that already exist. Each covers the entire United States--VLF more completely and usefully than VOR. Some

TABLE I

COMBINATION OF VOR-OMEGA OFFSET WEAKNESSES AND OPTIMIZE STRENGTHS OF BOTH SYSTEMS

VOR: VOR STRONG POINTS	ADVANTAGES OF COMBINATION	OMEGA: VLF (OMEGA) WEAK POINTS
1. 1,000 ground stations 2. Most aircraft equipped	Combination voids need for DME in air or more VOR stations	1. Almost no airborne units at present (all ground stations peoperational by 1974)
3. Voice channel to air to convey automated voice data (diurnal, barometric, etc.)	Voice automated diurnal from all VOR stations	2. Needs diurnal corrections
4. No ambiguities over 360°	VOR solves ambiguities and provides waypoints	3. Resolution of ambiguities
5. Familiar to all pilots	Use same type airway deviation display	4. New to pilots
6. Real estate, power, monitors, and telephone lines all in operation	Locate OMEGA monitors at VOR sites	5. Needs diurnal correction and monitor receiver each (area) 100 X 100 miles

TABLE I (Cont'd)

COMBINATION OF VOR-OMEGA OFFSET WEAKNESSES AND OPTIMIZE STRENGTHS OF BOTH SYSTEMS

VOR VOR WEAKNPOINTS	ADVANTAGES OF COMBINATION	OMEGA VLF (OMEGA) STRONG POINTS
1. Line-of-sight only	VLF prevents loss of airway guidance beyond line-of-sight of VOR	1. Beyond line-of-sight, and on surface
2. National coordinates are very complicated		2. Simplified national coordinates
3. Required DME for R-Nav	DME equivalency	3. Crossing LOP's gives distance data along airway-LOP
4. Requires altitude correction for many R-Nav services (references 30, 31, and 32) 5. Requires "3-D" airway computer	Lowers costs in airway computer	4. No altitude corrections needed 5. Simplified "oblique-parallel geometric computation of airways
6. Total R-Nav costs about 5 to 10 times VOR costs	Lowest economic level general aviation can afford; benefits many times costs	6. In production quantities should cost about twice the cost of a VOR receiver
7. Random spherical coordinates 8. Accuracy varies with range, azimuth, and individual station	Constant accuracy VOR supplies waypoints	7. Contiguous-coverage R-Nav by reception-only; little channel space required

would use VLF for tracks or airways and VOR for "waypoints" or longitudinal control of ATC. As far as spatial coordinates are concerned, VOR is a spherical coordinate system (when combined with DME). VLF-Omega retains vertical LOP's without need for costly-complex "spherical" corrections as shown in Figure 23. We are not suggesting a new navigational system, but a well-planned integration of the two existing systems so that the benefits of each are derived to create what might be considered a third system (VOR-Omega or "VORMEGA"), but one that seems to offer much more than either system alone. The combination for general aviation is much more suitable than competitive techniques, such as CAS, satellites, multilateration, etc.

Furthermore, the cost (a very critical criterion to general aviation) seems to be much less than "extrapolating" the VORTAC for general aviation. The cost of combining the VOR-Omega units in the typical general aviation aircraft to provide universal Area-Nav coverage will possibly be only ¼ as much as with VORTAC equipments, assuming we cater to the lowest stratum of general aviation economics.

C. SOME SPECIFIC EXAMPLES OF THE VOR/OMEGA INTEGRATION FOR BROADCAST CONTROL

Figure 24 shows an example of a single VOR station with the various lines of position derived from a typical VLF (wide baseline) system. The enormous literature available on Omega will show why so many LOP's in different directions can be derived from even a few stations (see reference 37). In example A of Figure 2, we see LOP-3 derived from VLF pair A-B, in example B we see the LOP-2 derived from VLF pair B-C, and in example C we see LOP-2 derived from A-D, etc. It will be seen that even if "raw" LOP data is used, many simple and highly useful combinations for "mixing" VOR and VLF coordinates exist.

Although it is relatively easy to use two VLF coordinates (crossing obliquely) to create a third set of coordinates in space, we will first examine the rudimentary combinations of VOR and Omega in their simplest form. Furthermore, it is a basic concept that may find acceptance because of its extremely low costs, and

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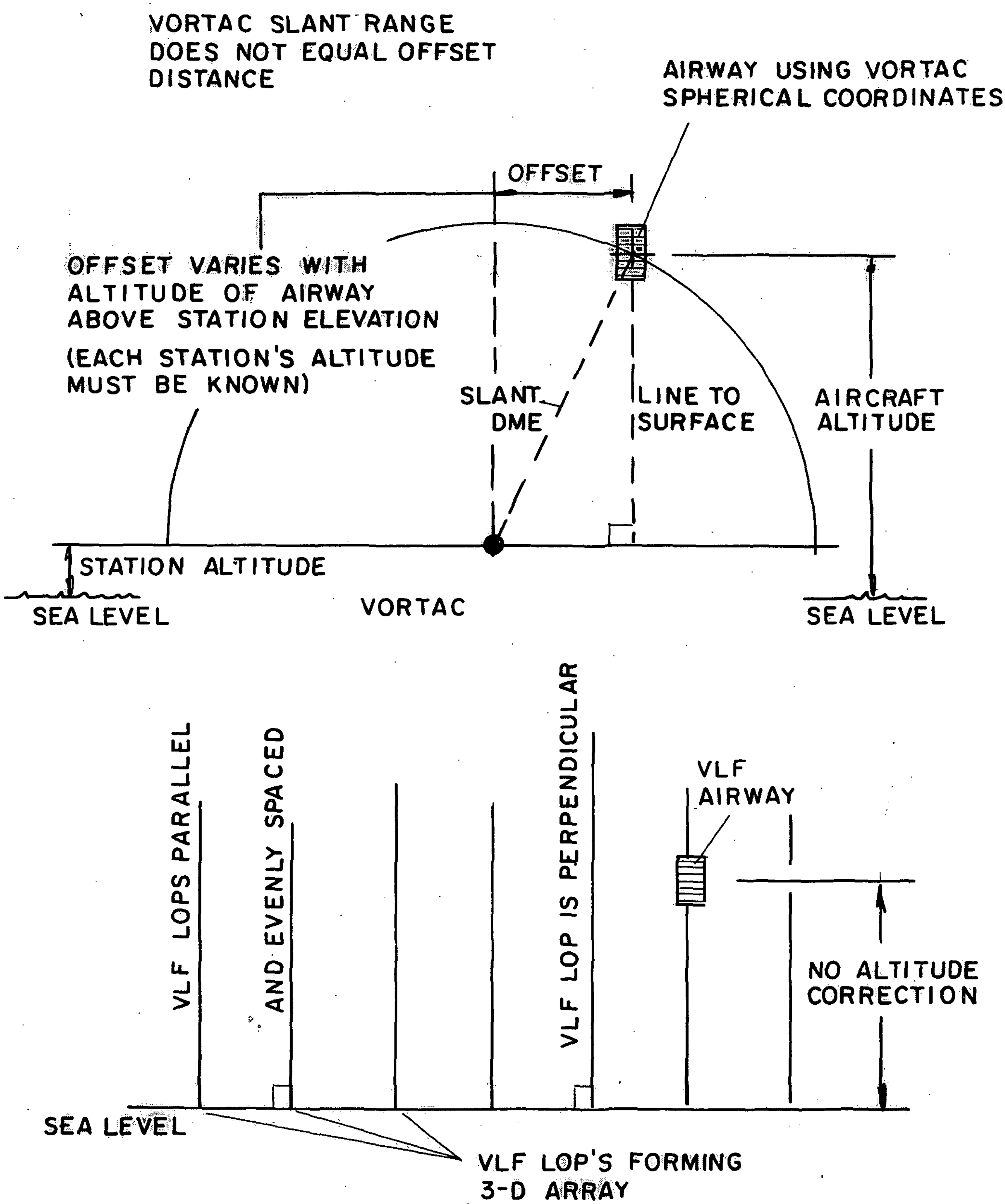


FIGURE 23 ADVANTAGES OF VLF's VERTICAL, PARALLEL LOP's OVER SPHERICAL (AND RANDOMLY LOCATED) COORDINATES OF VOR

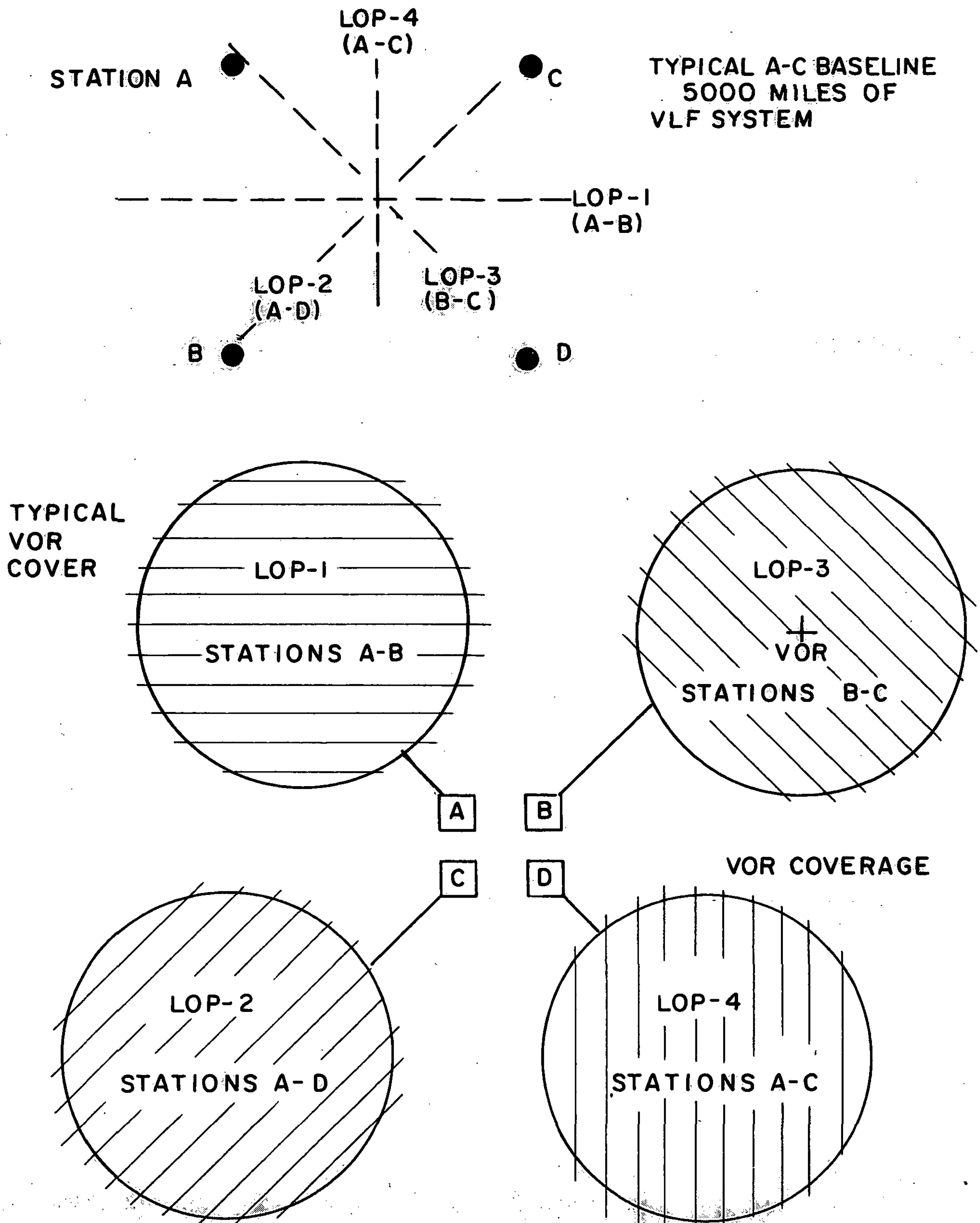


FIGURE 24 DIRECTIONS OF VLF (OMEGA) LINES OF POSITION IN A TYPICAL VOR COVERAGE DIAGRAM (NOTE ALL LOP's FROM A GIVEN PAIR ARE PARALLEL IN THIS AREA)

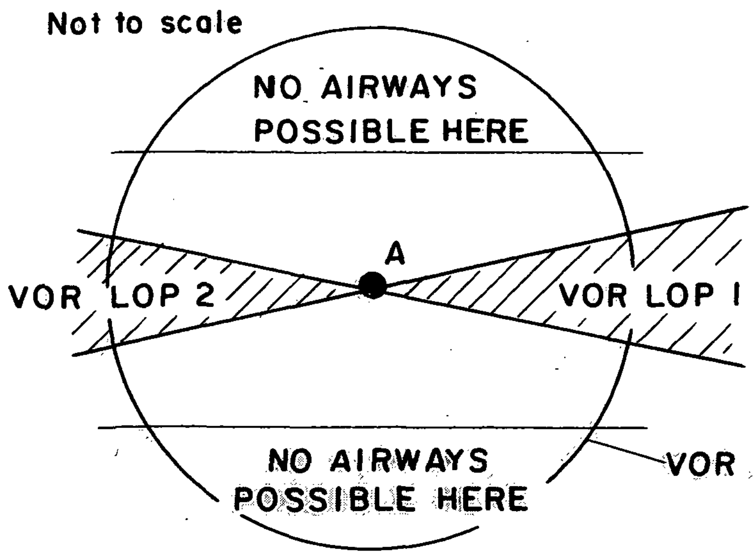
because it does not conflict with other users employing more sophisticated equipment.

As we have seen in Figure 24, we can have the selected VLF LOP's in any of several directions, within the coverage of a single VOR station. From an analytical view, this is equivalent to having 4 "Victor" airways emanating from a single point (in VOR), but with a most significant exception--we now have 4 airways emanating from any point we choose. This is a key point worthy of further explanation.

In Figure 25A we see (at the center of VOR coverage) the typical origin of a "Victor" airway at point A, which is the station or center of the circle for VOR coverage. Although VOR/LOP-1 is shown at 180 degrees to VOR/LOP-2, it is possible to establish these VOR-LOP tracks (today's airways) at different angles. However, in every case the VOR-LOP must pass through point A--that is, in a VOR/Victor airway configuration for ATC purposes, all airways must pass through point A, which is a most degrading and limiting factor in traffic capacity. This creates enormous loads on control of air traffic converging on point A that is unwarranted by the actual numbers of aircraft in the coverage diagram. No flexibility exists in the service area of a VOR airway.

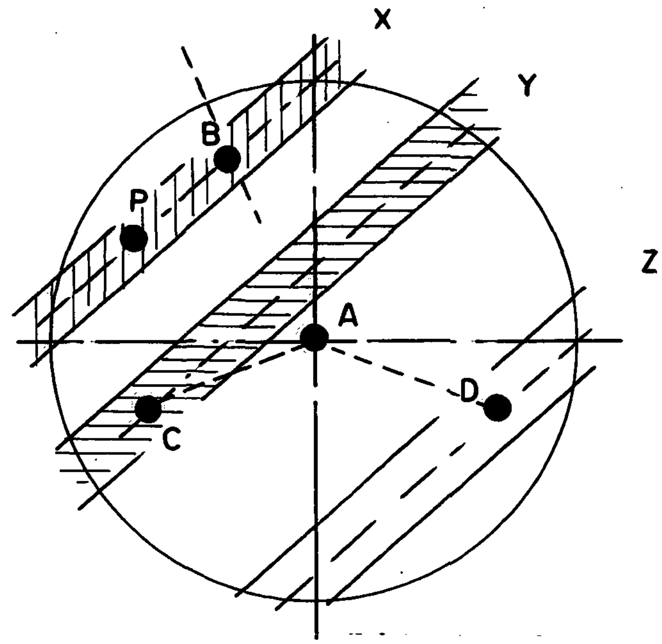
Furthermore, if it is desired to have several airways at many different LOP's, then they all converge at point A, creating traffic congestion, high risks of collision, and put unnecessary stress and workloads on pilots and controllers in dense traffic environments. To add insult to injury, seldom does point A lie near the origin of the flight, the destination of the flight, or even on a line connecting the origin and destination.

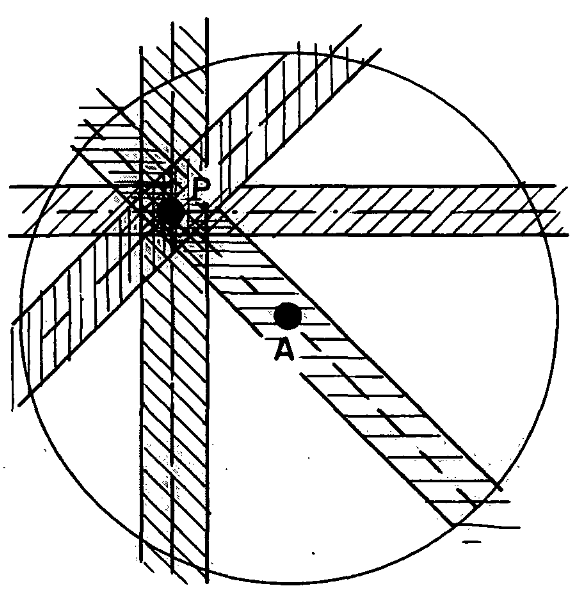
In Figure 25B we now see points B, C, and D that are created by our combined VOR/Omega concept of Airways. We see, for example, point B traversed with Omega LOP-2 (from Figure 23). We have created a nearly constant-width airway passing through point B and not point A. Also note that check points on the airway (X, Y, Z in Figure 25B) are provided by the VOR radials, so that no ambiguities exist. Being in the coverage of the VOR signals, the pilot uses the automatic voice recordings transmitted on the VOR that are controlled by an Omega "differential signal."



I
AIRWAY BASED ON VOR/LOP
MUST PASS THRU POINT A
AND HAS NON-LINEAR
SENSITIVITY

II
AIRWAYS BASED ON LOP-2
OF FIGURE 2 (VLF)
PASSING THROUGH
POINTS B, C, D,
AND P WITH CONSTANT
SENSITIVITY





III
OPTION OF AIRWAYS
PASSING THROUGH
POINT D USING
VARIOUS VLF/LOP'S
(SEE FIGURE 24)

FIGURE 25 EXAMPLES OF AIRWAY LOCATIONS IN A VOR COVERAGE DIAGRAM

A single Omega receiver in the area (about 100 X 100 miles) provides, on the telephone lines to the voice channel of the VOR ground station, the local VLF-diurnal correction. Also transmitted is other VOR-voice (automated) information suited to Broadcast type of ATC and airway scheduling. Using the VOR/Omega combination coordinates and communications functions, a dispersed, high-capacity, low-cost ATC system for general aviation is available, based on Broadcast control of that class of airspace user.

Thus, a pilot starting at point P or passing over point P on a direct flight is not forced to pass over point A as noted in Figure 25C. It appears as if we had the equivalence of a Victor airway system at nearly any point in the coverage of the universal VLF signals that fall inside the circle, and that we could have an airway in nearly any direction designated through any service point, which might be a small airport. Furthermore, the error that increases with distance along a VOR airway is avoided, since the actual right-left indication the pilot uses is the constant sensitivity VLF (Omega-type signal). The VOR is important, however, because it is used as a (1) back-up, (2) differential data source, and (3) cross-track fixing device or "waypoint" indication (more on "waypoints" later).

It will also be seen in Figure 25C that other points, such as C and D, can be serviced by this new, multi-direction airway concept. This avoids air traffic from concentrating at point A and, most importantly, from flying unnecessary distances, creating delays, unnecessary ATC loads, and convergency by being forced to pass through point A (as all Victor airways now do).

In Figure 25 (B and C) we see that the other LOP's of the VLF system each pass through points B, C, and D, just as they pass through point P, giving a choice of airway direction at these points. Again, this is nearly the equivalent of a VOR with 4 to 6 airways identified at each of these points. We have shown in Figure 25 an example of 3 points (other than point A) that can be served with 4 bidirectional airways each, or 12 bidirectional airways. This example can be expanded to cover perhaps 20 service points, each with the capacity of originating airways from that

specific point. Alternatively, an airway can pass through these additional points.

This clearly shows that the area of the VHF signal coverage is not utilized much more fully than in the radial-only concept of VOR that most of general aviation seems restricted to because of the high cost of VORTAC-R-Nav. The airways shown in Figure 25C are generated at much less cost than the addition of DME, R-Nav computers, altitude corrections, and complex coordinate conversions and charting of VORTAC-Area-Nav.

As we will stress later, the airlines already seem committed to VORTAC-Area-Nav, since the cost to them is small relative to their airframe and revenue generation capacity, but will probably remain excessive and overly complex for general aviation (the nearly 200,000 aircraft in the lower 85-percent economic strata). This potential of VORTAC-Area-Nav use by airline and other jets (business jets) is commensurate with their economics, flight profiles, and cruising altitudes as suggested in Figure 26. Business jets will outnumber airline jets by about 3 to 1 in 1980.

There tends to be a natural traffic segregation by aircraft types and flight performance (suggested in Figure 26). With VOR-Omega use by light (piston) general aviation aircraft and VORTAC-Area-Nav use by jets (business, DOD, and airliners), there is a harmonious relationship of airspace assignment, radio propagation advantages, cost advantages, and user benefits, optimized in each case for these widely divergent users of the national airspace.

This large cost and operational gap can best be filled by the separate use of (1) VORTAC and (2) VOR/Omega airways without serious problems of regulations, administration, or charting, etc., since VOR would be common to both schemes and 1,000 such stations already exist. This VOR/Omega concept may appeal to many, while an "Omega-only" concept may not seem as attractive since airway conflicts might be created. A true integration of both types of airways and ATC concepts is possible using VOR as a common element in both concepts. Low-cost use of vast new airways with Broadcast control techniques would be frustrated if only VORTAC-R-Nav is available and VLF's potential is not exploited.

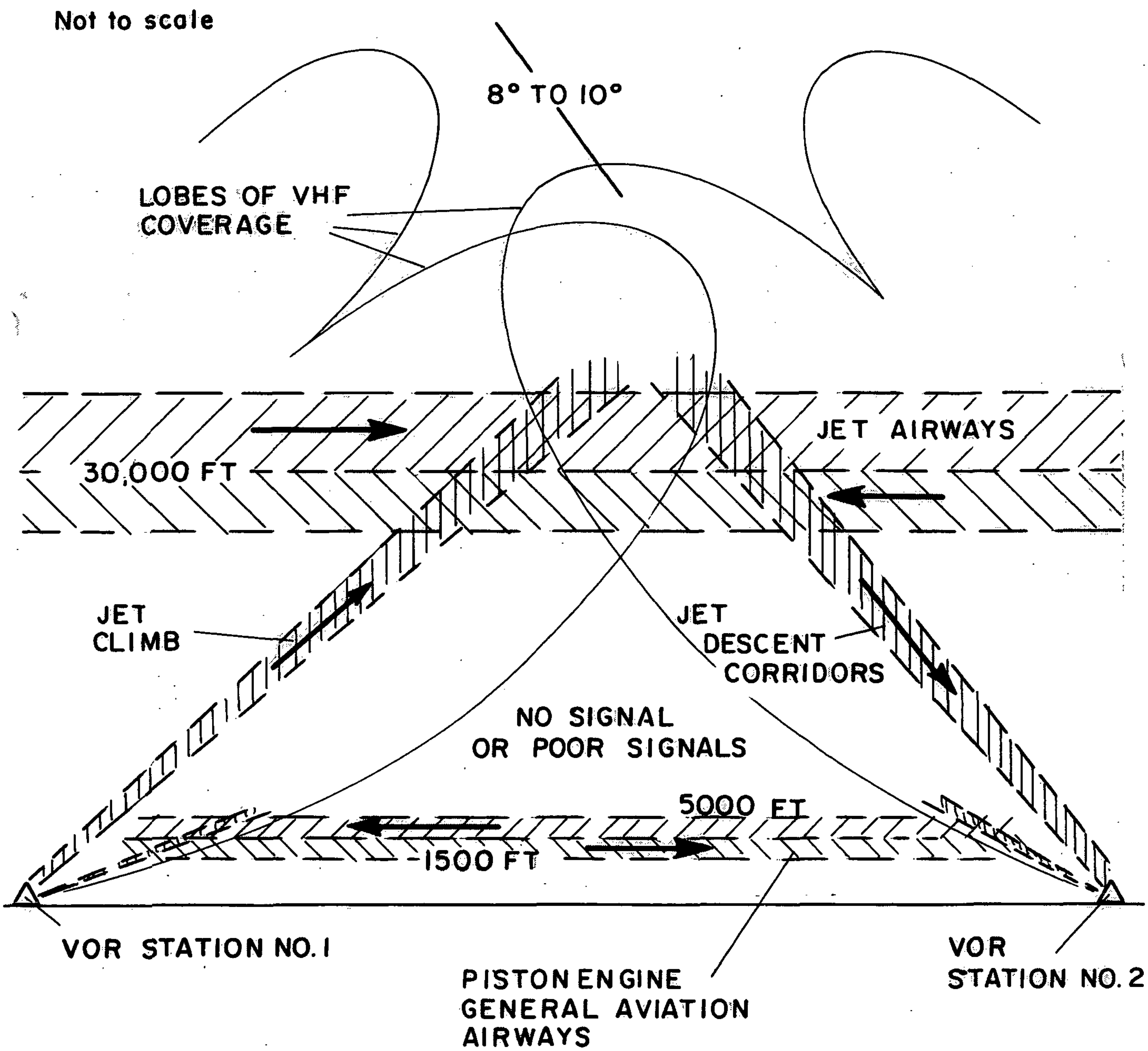


FIGURE 26 VERTICAL COVERAGE OF VORTAC SYSTEM IS MORE SUITED TO TYPICAL JET AIRCRAFT OPERATIONS OF CLIMB, CRUISE, AND DESCENT THAN TYPICAL GENERAL AVIATION PISTON AIRCRAFT OPERATIONS AT LOWER ALTITUDES

It is highly significant that the VOR/Omega marriage does not deny VORTAC-R-Nav; nor does VORTAC-R-Nav deny Omega/Area-Nav from developing. Each can evolve on its own relative merits and satisfaction of diverse users' needs. It is a way for technically, politically, financially, and operationally making use of the nearly 50 percent of the National airspace not now usable because of deficiencies in the airway structures, and to offer an airway emanating from every runway of every airport in the nation regardless of its size, location, or direction.

D. <u>EXAMPLE OF PILOT USAGE OF OMEGA/VOR SYSTEM OF AIRWAYS--"VORMEGA"</u>

In Figure 27 we see a simplified case of one VLF (Omega-like) LOP crossing the circular signal coverage diagram of a VOR station with its radial lines-of-position. We have two coordinate system overlapping radials and parallel lines-of-position. Let us assume that the pilot wants to go from point X to point Y in Figure 27. Looking on his airways charts, he sees the radial (compass-card) enscribed as on current charts; in addition, he sees a series of parallel and numbered LOP's overlaying the radial coordinates.

He sees, for example (Figure 27), that VLF LOP No. 7 passes through points X and Y. Assuming that he departs point X, he obtains (by tuning to the VOR station) the differential setting for the VLF signal eliminating any diurnal errors, since the differential corrections are given by automated voice reports every few minutes. A significant diurnal change usually takes about 15 minutes. He sees shortly after takeoff the crossing LOP radial of the VOR; this indicates that he is at a point on his flight path--that is, a designated airway--between X and Y. In Figure 27B we see his display; the right-left indication of the LOP-7 gives him a linear error presentation on either side of the airway centerline.

This VLF airway sensitivity is typically ±2 NM, according to some experts who have experience flying this type of VLF airway, but it can be any value from about ±1 NM to ±4 NM. In all cases, the airway width will have a constant sensitivity and linearity

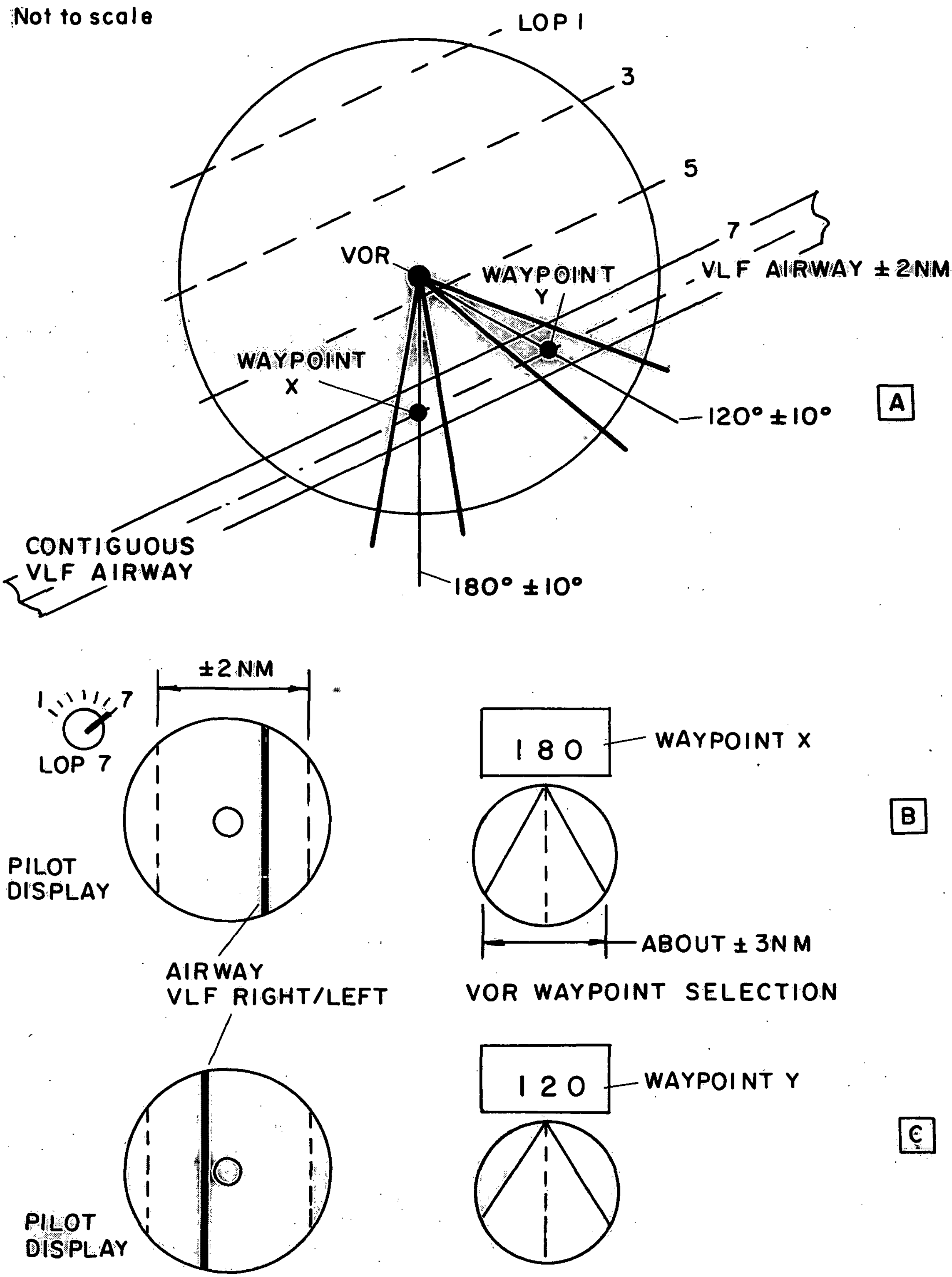


FIGURE 27 COMBINED USE OF VOR AND VLF (OMEGA) FOR WAYPOINT, DIURNAL CORRECTIONS

defining the flight path displayed by the Deviation Indicator. This infers that the pilot can, if desired, fly off the airway but exactly parallel to it, say, to descend into an airport with great ease. This is impossible with a VOR-only Victor airway deviation display, and this great potential of VLF precision-offset flight is of great significance to ATC procedures.

We see that the VOR display is used as it is now installed. By turning the radial selector to his first checkpoint (R-Nav waypoint shown as X) the pilot is shown a cross-bearing of 180 degrees (see Figure 27). Since the VOR indication (full scale to full scale) is normally about ± 10 degrees, we have an excellent display of (1) anticipating the closing to and arrival at the waypoint or checkpoint, (2) its exact location, and (3) the passage beyond it. If, for example, the tangential distance of track 7 (VLF) is about 18 NM from the VOR station, then the ± 10 degrees is equivalent to about ± 3 miles on either side of waypoint X.

The pilot continues with ATC concurrence on the track (airway) and now wishes to arrive at waypoint Y, which for purposes of explanation could be a radial of 120 degrees. Again, the VOR radial displacement indicator is shown in Figure 27C, and we note that the pilot will have again an anticipation signal about 3 miles (maybe 4) from the waypoint, an exact indication of the waypoint, and then his distance beyond the waypoint. Obviously, airway charting would establish these waypoints, but the pilot workload is kept minimal, possibly half of that using VOR-only techniques.

E. PILOT WORKLOAD USING VORMEGA (VOR/OMEGA COMBINATION OF AIRWAYS)

Essentially, the pilot has a contiguous, easy to fly path displayed to him on his airway deviation indicator. Since the airway itself is a VLF origin (2 stations about 4,000 to 5,000 miles apart), it stretches for hundreds of miles without pilot adjustment. For practical purposes, it is straight-through for 100 miles, but with a long curve of parallel lines when examined over a stretch of, say, 1,000 miles. Since waypoints are usually less than 100 miles apart, the pilot has a very low workload when he

has selected his airway (No. 7 above using LOP-2 of stations A and D--Figure 24). Next, he must set in his waypoints using his VOR receiver. This is less demanding than using a single VOR receiver for obtaining dual VOR "fixes" for crossing VOR bearings (wherein one is lost while the other is being measured). The pilot thus leisurely sets up his next waypoint, sees it arrive in the window of the VOR deviation indicator (Figure 27), pass when it is zeroed, etc. (giving him anticipation, indication of exact passage, and distance beyond the waypoint).

Next, he tunes the bearing selector of the VOR receiver to the next waypoint, which is another VOR bearing crossing the (unmodified) VLF settings. Thus, at no time does he modify or lose his actual airway-track deviation indication while obtaining a "cross-fix" or waypoint. The pace is slow so that a single pilot in a typical light aircraft at its usual speed should have less workload with "VORMEGA" airways than with VOR Victor airways or with VORTAC using R-Nav airways.

Although it would seem simple to use the two separate displays (as shown in Figure 27), a combined display of VOR radials and a linear deviation indicator might be helpful, so that one would have a typical "area" display showing the analog of the localized area surrounding the waypoint (in the center of the display). In Figure 28 we see that this is readily displayed with only slight distortion, so that the pilot can use the 4 X 4 miles (or 6 X 6 miles) of displayed area for, say, a turn, descent into an airport, maneuver onto a new airway in another direction, or to a new waypoint, etc. To optimize these two and similar display methods will require some actual simulator and flight test measurements. However, as in most instrumentation of Area-Nav concepts, the specific form can vary in order to meet acceptable cost levels, pilot requirements, operational needs, etc., without changes in the basics of the concept.

In fact, if the concept of marrying Omega and VOR were not adaptable for at least two to three forms of conventional instrumentation (at different cost and workload levels), it would be a weakness in the concept. Constraining the success of an ATC concept to a single, unique (and possibly costly) pilot display

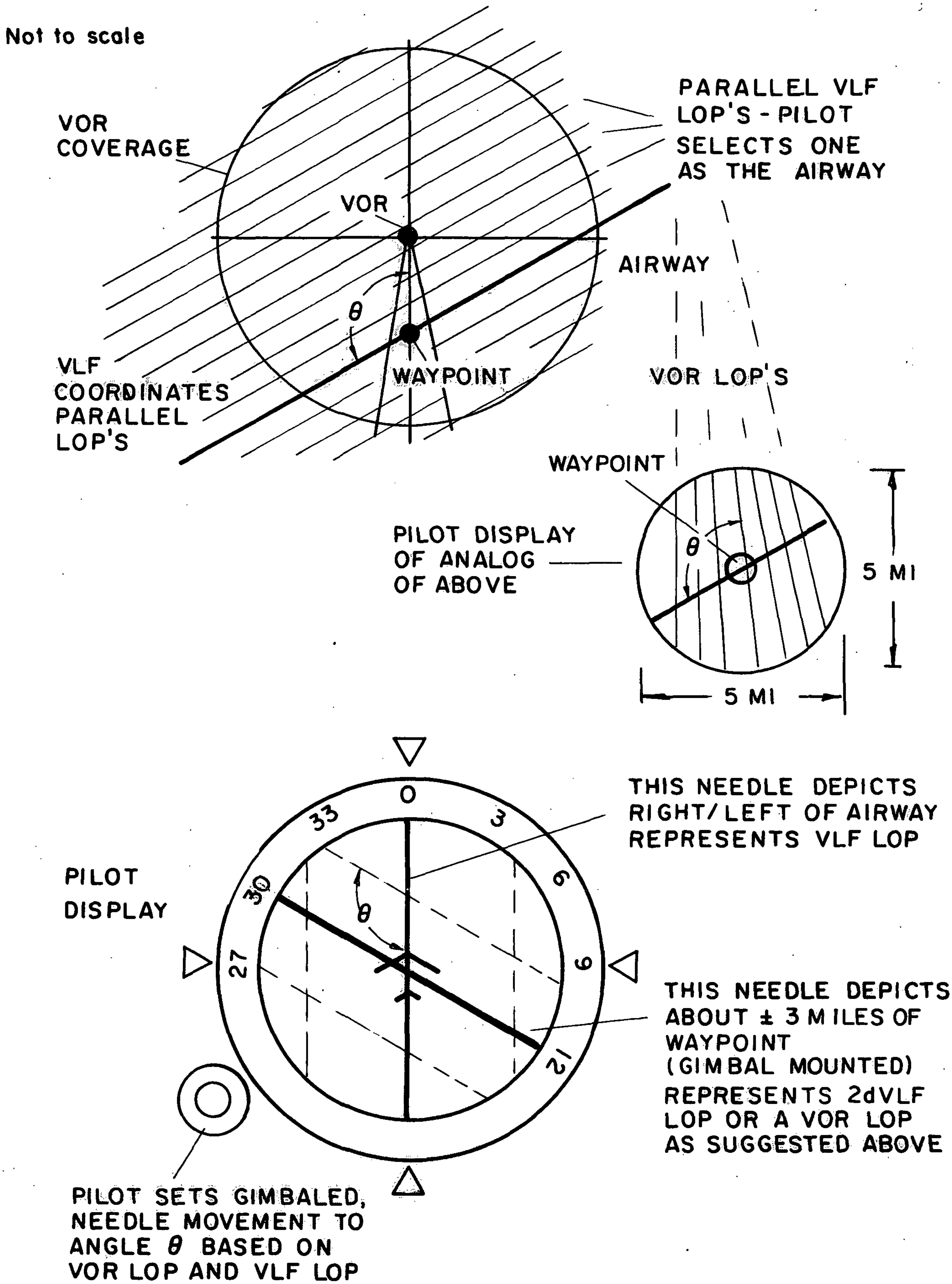


FIGURE 28 PILOT DISPLAY INTEGRATES VOR/VLF (OMEGA) AIRWAY DATA

technology is a sure way to assure minimum usage and inability to get national acceptance. Different engineering concepts and manufacturers will prefer various forms of displaying the new VOR-Omega concepts of Area Navigation. Some of the current R-Nav displays in the low-cost brackets would be good candidates for the VORMEGA display.

F. AIRLINE USE OF AREA-NAV BASED ON VORTAC AND BAROMETRIC CORRECTION

The above discussion is aimed mostly at the 85-percent light aircraft population of general aviation that will number nearly 200,000 by 1980. The recent national conference on VORTAC (early in 1972) Area-Nav and Inertial Area-Nav indicated that enormous interest in the subject exists among pilots, engineers, administrators, etc., with over a thousand experts attending this two-day FAA symposium on the subject. Several references indicate the advanced stage of airline thinking on this subject (references 12, 30, 31, and 32). Several manufacturers have developed R-Nav computers that cost several tens of thousands of dollars and fit the VORTAC inertial interface.

References 12, 30, 31, and 32 provide a good review of the airline and FAA plans. Considering the emphasis and needs of airlines and the different cost-benefit criteria between a 15-million-dollar jet and a 15-thousand-dollar light aircraft, it is likely that the airlines will proceed to use VORTAC-Area-Nav in the near future. Reference 31 notes that the various levels of sophistication in R-Nav (computers only, not VOR, DME, etc.) are Mk I--$15,000 to $30,000; Mk II (including a digital computer)--$40,000 to $80,000; and Mk III (expansion of inertial-VORTAC interface)--$110,000 to $150,000. Considering the savings in routing, pilot workload aspects, need for vertical navigation in airlines, and worldwide needs (inertial and other coordinates besides VORTAC) all of which can be realized by the Mk II and III computers, these cost figures are not inconsistent with the worth of this service to the airlines.

From the view of the lower 85 percent economic strata of general aviation aircraft, even the simplest Mk I unit is beyond the reach of the user. Many other demands on his resources for

ATC (such as transponders, altitude reporting in 1975, PWI, MLS, data communications, etc.) are of equal significance to the potential user as R-Nav. These users cannot afford all of the new avionic systems and will accept voluntarily only those where the benefits outweigh the low costs (such as the 50,000 transponders costing in the $600 to $1200 range).

The main point being made here is that it is possible to encourage these users (who may make up half the airborne aircraft in the 1980 to 1990 time frame) to use Area-Nav of the VOR/Omega type, since it will require only the addition of a VLF receiver that costs slightly more than a VOR receiver. This additional receiver will cost about $1,000 to $2,000 when production approaches the VOR receiver volume.

G. GENERAL AVIATION AIRWAYS AND AIRLINE AIRWAYS

From the above it is possible to postulate the use of VORTAC by the airlines. It fits their flight profile as seen in Figure 26 where the climb and descent profiles to high altitudes are more commensurate with the vertical lobe structures and signal coverage of the VHF line-of-sight system of VOR at about 100 MHz (and DME at 1,000 MHz). To the side and parallel to these airways can be defined new airspace for general aviation use that is authorized for the exclusive use of certain classes of slow low-performance aircraft operating below (about) 10,000 feet. The jet aircraft is excluded from this airspace because of its speed, climb corridors, and other differences. Although reference 31 notes the difficult pilot workload in setting in and using waypoints in a jet airliner, these same problems are much less severe in a light, slow, general-aviation aircraft (say a light-single). With speeds differing by about 4 to 5 times, the pilot must reset, retune, etc., much more frequently in a jet, and thus the high workload exists.

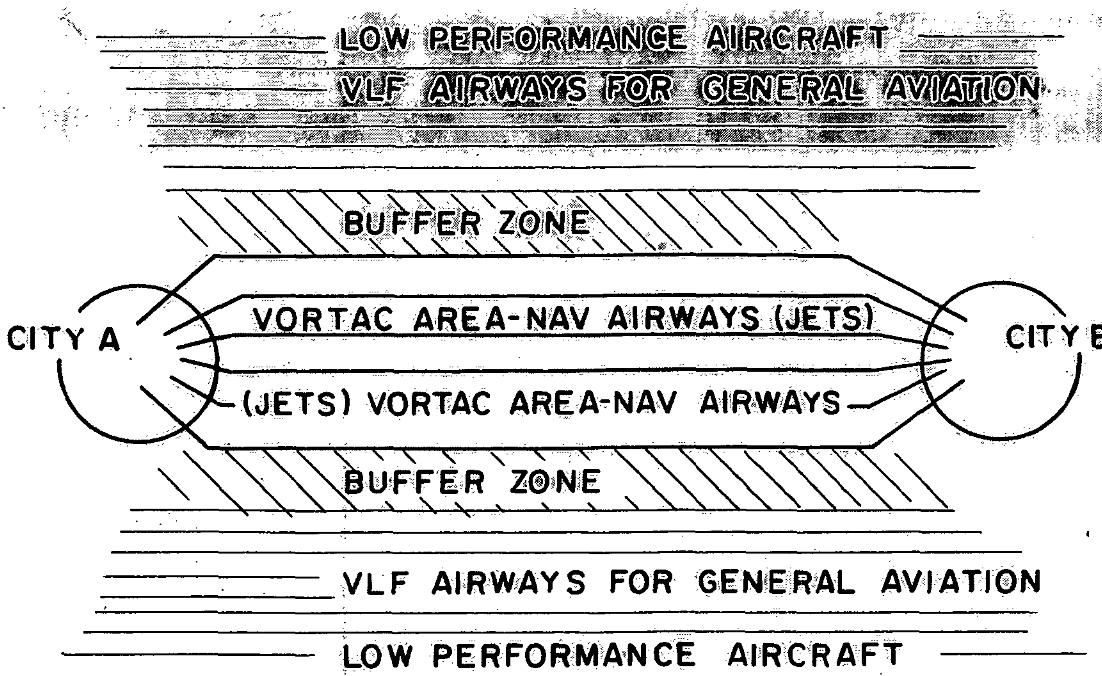
Furthermore, the jet cruising at 30,000 feet needs "vertical" navigation, complicated inputs using three-dimensional VORTAC data from several VORTAC's, and barometric altimeter inputs. This is complicated and costly but nevertheless essential to jet operations to gain fuel efficiency and speed in cruise conditions

on a direct R-Nav airway where dozens of VORTAC's are involved. This is something the light-single does not need. Thus, many of the assessments by airline engineers of R-Nav do not apply to general aviation, and their pioneering effort indicates that the price is suited to airlines but beyond 90 percent of general aviation aircraft owners. If airlines hope to conform to the VORTAC-R-Nav airways, as the FAA now sees them (reference 32), it will be essential to find new airspace for general aviation.

It is, therefore, suggested, as in Figure 29, that about 8 miles beyond the jet airways and at altitudes well below them, a general aviation airway system be authorized using the two national (funded and existing) systems (in 1974) of VOR and Omega. Each requires no added channels and no new transmitting channels; furthermore, these two systems require only simple receivers, each costing about $800 and $1500 respectively, but this will perhaps nearly double the amount of useful airspace to general aviation on a national basis.

The concept of VFR flight anywhere is rapidly vanishing, if not already extinct. So many controlled areas (volumes) of airspace exist that merely excluding a party from them is no longer safe, since they are numerous and geometrically complex in their (three-dimensional) authorization and identification requirements. What is needed is a new airways approach to the use of vast amounts of unused airspace, so that it is defined in three dimensions for general aviation use. This will segregate high- and low-performance aircraft which, when mixed, are the major source of mid-air collisions and air traffic congestion.

VLF signals can reach any altitude of concern to general aviation (piston). These signals are also available on the surface, allowing a new concept of pilot usage--ground calibration using the actual airway signals just prior to takeoff--something impossible with VOR. This characteristic of VLF propagation adds credibility to the concepts of "Broadcast Control," since the pilot can adjust his climb-airway prior to takeoff and follow it without airborne tuning. By paralleling what some call "VFR airways" with the VORTAC airways, it is possible to give general aviation users a much required service, since most of their



JET TRAFFIC USES VORTAC AREA-NAV AIRWAYS TO SERVE JETPORTS IN CITY A AND JETPORTS IN CITY B

LIGHT AIRCRAFT (LOW SPEED, ALTITUDE, COST) UTILIZE VLF AIRWAYS ESTABLISHED PARALLEL TO JET AIRWAYS.

VLF SERVES HUNDREDS OF OUTLYING AIRPORTS AND LOW ALTITUDES

FIGURE 29 UTILIZATION OF VLF AND VHF AIRWAYS FOR HIGH AND LOW PERFORMANCE AIRCRAFT

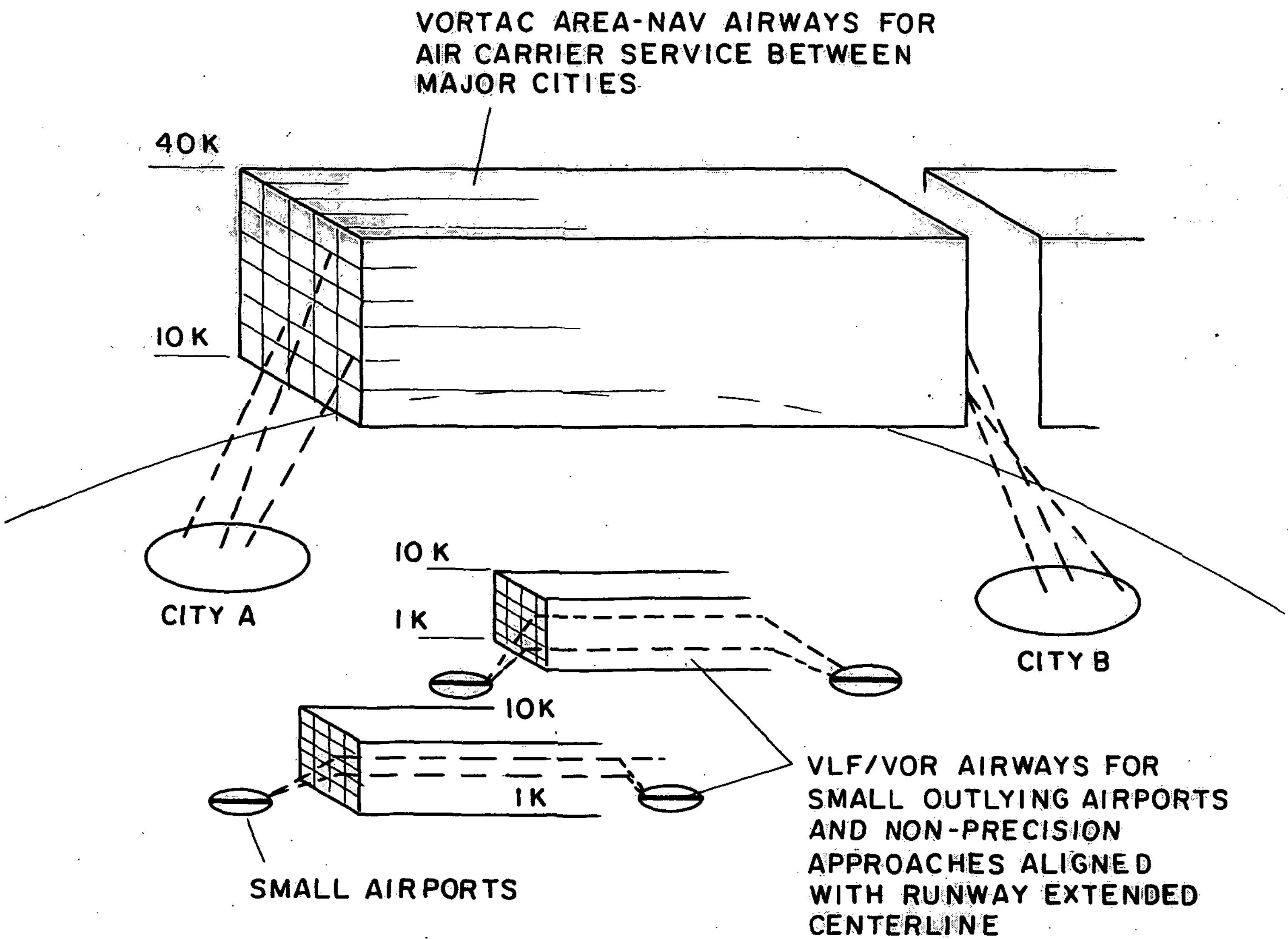
destinations are increasingly to some other airport than the jetports. The business jet is likely to comply with airways much like airliners, but it will also serve the intermediate airport that has poor airways. Figure 30 emphasizes this point.

Admittedly, when the general aviation aircraft is not near the heart of VOR coverage (as the airlines will be, since VOR siting usually was predicated on this type of service), we will not have as good coverage from VOR as we might like for the "VORMEGA" concept. However, by integrating Omega with VOR, this weakness is overcome operationally. Omega is available continuously, whereas VOR will be unavailable at times depending upon geography, station location, and altitude of the general aviation airway complex.

Even though intermittent inputs exist from the VOR for the integration functions with VLF Omega, the continuous nature of VLF coverage overcomes this VHF deficiency and yet gains from the benefit of the VOR data when it is available. As was shown in Table I, VOR signals (voice) are used to (1) periodically update the VLF diurnal data, (2) obtain waypoints, (3) assure that the two coordinates (VLF and VHF) are tied together, and (4) as a means of exercising some form of very-low-cost yet semi-automated traffic control, based on the principles and concepts of "Broadcast Control."

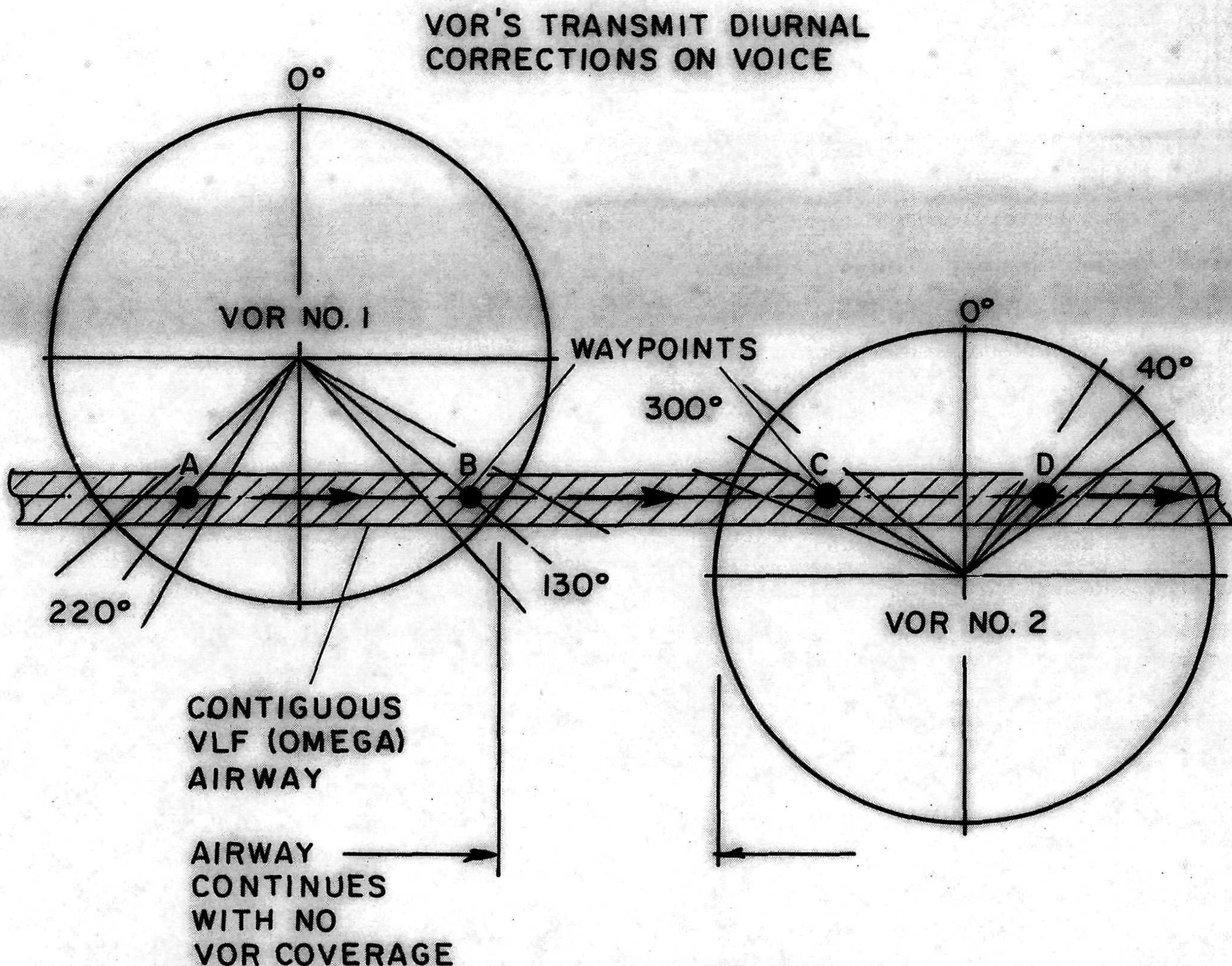
In "Broadcast Control," the pilot follows an authorized VLF/VOR airway as does all traffic going between service points. In doing this, the airway is identified as one of several parallel airways and one of several altitudes; the airways are so codified and presented in flight charts and manuals to the general aviation pilots. The airway is then divided longitudinally into "blocks" to attain a three-dimensional block of airspace. Thus, each airway is a series of blocks of airspace defined and coded for pilots in three dimensions.

It will be seen in Figure 31 that the actual centerline and boundaries of the airway are determined by the VLF(Omega) signal. At takeoff, the pilot "zeroes out" all VLF errors, knowing the airport location and the fact that the airway starts at the threshold of his departing runway, something we can do with



FIGUR 30 COEXISTENCE OF TWO AREA-NAV SYSTEMS OPTIMIZES AIR CARRIER USES AND PROVIDES GENERAL AVIATION AIRWAY AND APPROACH SERVICES TO OUTLYING SMALL AIRPORTS, THUS AVOIDING MIXING OF LOW AND HIGH PERFORMANCE TRAFFIC THAT CREATES HIGH ATC COSTS AND HAZARDS

Not to scale



INTEGRATION OF VOR AND VLF (OMEGA) PROVIDES

1- MEANS OF CONTINUOUS AIRWAY TRACK WITHOUT BREAK DUE TO VHF (VOR) COVERAGE LIMITATIONS

2- PERIODIC DIURNAL CORRECTIONS FOR VLF AIRWAY

3- CONSTANT AIRWAY SENSITIVITY AND VERY LOW ALTITUDE AND SURFACE COVERAGE

4- INDEPENDENT WAYPOINTS COORDINATED WITH VORTAC AREA-NAV

5- LOW-COST AIRWAYS THROUGH ANY POINT WITHOUT "3-D" COMPUTER

FIGURE 31 MERITS OF VOR/OMEGA INTEGRATION

VLF but that is impossible with VOR or VORTAC. Next, he climbs on an airway that is an extended centerline, avoiding turns (unless occasional other requirements exist, such as a curved noise abatement airway procedure). Next, while enroute, he tunes to the VOR signal associated with that specific (VLF-VOR) airway and obtains "cross-fixing" data, or what is now called "waypoints" in the new "R-Nav" language.

This procedure has the double benefit of obtaining the voice data on the VOR (simultaneous voice), as well as providing an independent means of establishing the waypoint (which may also be established with VLF, since VLF has coordinates that cross the airway obliquely). If a failure in VOR occurs, the pilot continues on VLF; if a failure on VLF occurs, the pilot reverts to VOR usage, holding his heading to the waypoint and then reverting to the standardized VOR navigational procedures. Two linear LOP systems can achieve this complementary and "fail-safe" service, which a circular LOP (DME) cannot provide, with equal utility and credibility.

Although VOR stations are occasionally off the air for various reasons, a more important and irksome failure of VOR service is signal "dropouts" and its unavailability on a continuous basis. Signal "dropouts" occur between stations as shown in Figure 31. Here the pilot has used two waypoints (A and B) to check his location and to comply with ATC (each segment of the airway is a "block" such as A-B, B-C, etc.). The pilot then dead-reckons longitudinally between waypoint B and waypoint C where no VOR coverage exists.

This is a partially "open-loop" ATC (only for a known time and then only longitudinally), because his direct airway signal is not lost since it is a VLF signal and is continuous across the nation at all altitudes. However, for ATC purposes block B-C, even without VOR coverage, is treated the same as block A-B--that is, occupancy is not permitted by another aircraft until the first aircraft clears past waypoint C, which by that time is in the VOR range of station 2. Upon returning to station 2, the pilot acquires waypoint C and "anticipates" the passage for the last 3

miles, using deviation indications as shown previously in Figures 27 and 28. He also acquires a new diurnal (differential Omega) input from the voice data on VOR-2. Since the pilot may now have traveled some 100 miles from the original diurnal input, time and location have modified his "differential" Omega input, and it is now updated. Once this new "differential" data is used to update the VLF reference for the coverage area of VOR-2, the pilot proceeds to waypoint D, etc.

The VOR data will serve as a cross-check on the VLF-longitudinal-LOP data, since both sources of waypoints are used. The pilot essentially has a continuous back-up on waypoint data in the dual low-cost and simplified use of the VOR and Omega coordinates.

Since so many small airports will never have an ILS or even an airway near them in the current VORTAC concepts, this technique of a second Area-Nav system for general aviation offers needed service and Broadcast Control of air traffic to some 10,000 small airports. With an airway structure that is much easier to use in the cockpit and much safer than VORTAC alone, back-ups and "co-monitoring" of both systems occur in their usage, giving pilots confidence in their use and assuring him that the weaknesses of each system alone (Table I) do not deny safety. The workload is much less for the general aviation pilot, since the VLF airway is initially aligned with the departing runway, and signals reach the departure climb from the beginning. Similarly, the arriving runway is served without the complexity of divergent approaches and the high risk of "VOR let-down" that has now been identified as one of our major accident sources. The dangerous "circling approach" will be a thing of the past with the adoption and use of "VORMEGA."

VIII. BROADCAST CONTROL USING VHF-COM AND VHF-VLF AREA-NAV

The pilot using a low-cost tone data signal (a $100 unit paralleling the microphone input to his VHF-COM set) solicits the ground regarding the occupancy of the next adjacent airway block (as shown in Figure 31). If the block is unoccupied, the aircraft (via a decoded automated voice message, much as the telephone company uses for time signals) clears the aircraft. The voice and timing also confirm the aircraft's identity. Any further requests for the specific block will be denied until the aircraft clears the airspace of the airway block by another pushbutton selection, soliciting authorization to enter the next block of airspace.

Two nearby pilots can actually hear each other's instructions and aid in air-to-air supervision. This is one of the important precepts of Broadcast Control. The ground system is a simple and low-cost relay-electronics; interlocking assignments; is a system that is a relay analog of the airway. Possibly a "mimic-board" placed at the Flight Service Stations (FSS) near the airways would also assist, since FSS personnel are used in Broadcast Control.

Thus, the pilot progresses to his destination through sequential airway blocks, and if denied entry into one block, he holds (circles) within his currently assigned block of airspace. ATC radar vectoring is avoided if the pilot navigates and controls under Broadcast ATC rules. This concept of "block signaling" was partially engineered into the FAA airway system (then CAA) in 1948-1952, but became too slow for the much faster turbo-jet aircraft. The arrival of the jets forced major changes in ATC, yet block signaling could now be revived for the much slower, low-flying, light aircraft of general aviation.

A detailed engineering design of such a system is beyond the scope of this report, but the fundamental elements on which it is based already exist in the coverage of the VOR and Omega systems, the VHF-COM network, and the multi-tone data reporting from the aircraft. No new technology is required, but a "total system" approach to the problem is needed to optimize on an evolutionary basis what is available today. The concepts of Broadcast

Control offer a new means of dispersion of air traffic by creating new airways in airspace not now utilized but essential to the growth and safety of general aviation. Utilization of this new airspace does not now appear possible with VOR or VORTAC R-Nav. The costly application of VORTAC R-Nav to aviation may be accepted by the airlines but is beyond the reach of most of general aviation because of the prices of nearly all VORTAC R-Nav equipments. Two national R-Nav systems seem inevitable: one an airline system based on VORTAC inputs costing from 20 to 100 thousand dollars per aircraft; the other a system based on VOR/Omega equipments costing about 2 to 3 thousand dollars in production quantities.

A. AIR/GROUND COMMUNICATIONS IN BROADCAST CONTROL OF AIR TRAFFIC

In many concepts of ATC, such as "radar vectoring," it is essential to convey a great deal of information between the pilot and controller. This infers in many cases a modernization of communications, using an automated data transfer system (often called a "data link"). Currently the FAA is considering a means of adding an "up-link" to the SSR transponder system. Such a ground-to-air link would complement the current air-to-ground link coverage of 8,000 codes relating to altitude and identity. A coded message on the up-link of 40 to 60 bits would be necessary to accommodate the address, command, quantity, and parity checks.

This Discrete Address Beacon System (or DABS) is very costly and tends to further emphasize the concepts of "Close Control," where the ground authority commands, and the pilot is little more than a lackey in the system. Such concepts add increasing burdens on ground "automation," remove the enormous value of voice, and increase costs and complexity to a point where nearly all of general aviation is effectively denied such services.

The intent here is to stress the need for a low-cost Broadcast Control system that avoids these pitfalls in national planning of airspace usage. A VLF grid, either entirely new (being designed for the contiguous 48 states) or a marriage of existing VOR and VLF/Omega in the 1974 period, is a more likely solution. Both services will then exist across the entire nation and will be

available for ATC with low-cost airborne units. This marriage might be termed "VORMEGA," and we have already identified several advantages and virtues of the concept. Essentially, the weaknesses of each system are overcome when combined to make VORMEGA suitable for a low-cost "Broadcast Control" coordinate system. The strengths of Omega overcome the weaknesses of VOR. The weaknesses of Omega are overcome by certain VOR characteristics. Viewed from the joint applications in VORMEGA, we have two independent back-ups (VOR and Omega) that can be used to create linear LOP's separately.

DME is avoided with its complexity, need for costly R-Nav computers, complexity of a multiplicity of spherical coordinates, and lack of linear tracks from DME only (when VOR fails). Effectively, general aviation can be provided a total Area-Nav system in VORMEGA that is universally available across the nation for a small fraction of the cost of VORTAC R-Nav. The airlines, because of other large benefits relative to cost considerations, nature of the flight patterns of jet aircraft, etc., may well utilize R-Nav with VORTAC on the nation's high-density air routes. VORMEGA will then allow an alternative since these routes will not use the low-cost VOR "radial tracks." Table II outlines the compatibility of Broadcast and Close Control concepts of Air Traffic Control.

Denying the VOR radial service on dense airways, we now allow general aviation the use of a much expanded airways-ATC airspace alongside these jet R-Nav routes and relieve their loads by using VORMEGA. Costing possibly only 20 percent of the VORTAC solution, the airlines and general aviation of all classes will comply with a new airways ATC concept.

In any event, Area-Nav--whether based on VORTAC, based on Omega, or based on the VORMEGA concepts--has one goal in mind: placing the pilot back in the ATC loop where he belongs and where he can do specific ATC jobs better than the controller. Much improved tranquility of mind is obtained when flying in separated airways over the concepts of Close Control where some "black box" commands him without his ability to exercise his judgment, establish the credibility of the ATC command, or even be aware of the commands to other aircraft in his proximity.

TABLE II

COMPATIBILITY OF "BROADCAST" AND "CLOSE" CONTROL CONCEPTS OF AIR TRAFFIC CONTROL

1. AIRLINES AND JETS USE VORTAC, PARALLEL AIRWAYS CREATED BY THE USE OF VOR, DME, R-NAV COMPUTERS, ALTITUDE CORRECTION, AND ABILITY TO DISPLAY VERTICAL AND LATERAL AIRWAYS (3-D).

2. LOWER 85 PERCENT ECONOMIC STRATA OF GENERAL AVIATION WILL USE A COMBINATION OF EXISTING VOR AND OMEGA SYSTEMS WITH GREATLY SIMPLIFIED COMPUTER AND DISPLAY POSSIBLE WITH THE MANY COVERAGE AND "GEOMETRICAL" ADVANTAGES OF "VORMEGA."

3. AIRLINES CONTINUE TO USE "CLOSE" CONTROL CONCEPTS OF RADAR-VECTORING AND POSSIBLE USE OF "DABS."

4. GENERAL AVIATION UTILIZES "BROADCAST" CONTROL CONCEPTS BASED ON GREATER FLEXIBILITY OF VORMEGA AND THE UNIVERSAL NATURE OF ITS COVERAGE FOR AIRWAYS AND NON-PRECISION APPROACHES ALIGNED WITH UP TO 30,000 GENERAL AVIATION AIRPORT APPROACHES.

5. AIRLINES USE HIGH-DENSITY ROUTES BETWEEN MAJOR CITIES AND AT HIGHER ALTITUDES WITH SLANT-AIRWAYS OF CLIMB-DESCENT CORRIDORS FOR JET OPERATIONS.

6. GENERAL AVIATION USES LOW-DENSITY AIRWAYS ESTABLISHED BY THE VORMEGA AND BROADCAST CONTROL BASED ON BLOCK SIGNALING.

7. AIRLINES ARE CONTROLLED BY GROUND ATC THROUGH THE TRANSPONDER, R-NAV, GROUND RADARS, COMPLEX COMPUTERS, DATA LINKS, AND THOUSANDS OF CONTROL PERSONNEL AT CENTERS AND TOWERS.

8. GENERAL AVIATION TRAFFIC MOVES ON DISPERSED AIRWAYS SEPARATED FROM ITS OWN KIND AS WELL AS AIRLINES, AND DISCIPLINE IS MAINTAINED BY BROADCAST CONTROL. THE PILOT, USING TONE-DATA ON VOICE CHANNELS, SOLICITS AIRWAYS AND APPROACHES WITH LITTLE OR NO GROUND PERSONNEL INTERVENTION.

In reference 31, American Airlines reports from a great deal of experience shared by other airlines that the R-Nav concepts reduce communications by as much as 25 percent and can reduce both the controller and pilot workloads. In fact, AA experience indicates that radar monitoring of R-Nav routes is not necessary, thus off-loading the ATC controller. The pilot, of course, following his displayed three-dimensional airway to the mandatory reported waypoints, feels strongly that more authority and capability must be restored to the cockpit if we ever hope to solve our ATC problem. Even though individual pilot complaints about R-Nav prevail, it is evident from the recent symposium that they prefer the concept of R-Nav in ATC rather than more radar-vectoring by automated ground computers and data links.

The question remains, however, as to how the pilot will communicate in the new Broadcast Control concepts. Even though the communication load will be less, it is important that modern communication advances also be considered as part of the control system. In our case of general aviation, it is suggested that we consider use of a fully developed new technique in voice communications, such as the dual-tone data transmission system used in the A.T.& T. system. Tone data solicitation from the air and automated canned-voice messages from the ground avoid the need for a costly airborne data-link receiver.

Where it may cost \$50 to \$100 for the 4 X 4 dual-tone system (one of 16 combinations in a 50-millisecond tone burst) for an airborne unit, the ability to decode up to 4,000, or even perhaps 100,000 tone data messages requires ground equipment that is costly. However, a single ground unit serves up to 50 aircraft, greatly reducing total costs, since under the recent "user" tax the pilot pays for both the air and ground units. Furthermore, we have a firm national commitment (as a part of the SSR-transponder program) to add altitude reporting by 1975 in nearly all aircraft. This is another major means of also sending messages of identity, altitude, position, emergency, acknowledgments, etc., to the ground system, which we may want to apply sometime in Broadcast Control. The SSR is a fully developed system; however, some modest changes

in communications are needed if Broadcast Control of a vast new airway capacity is to become a reality.

As noted before, it is possible, using very-low-cost VHF-COM capacities already available (but needing organization), to solicit the use of an airway segment between two waypoints (Table III). This solicitation is acknowledged by the automated voice from the ground, and the interlocks of a simple relay-type system prevent any other commitment of this R-Nav segment until it is released by the first aircraft. Thus, if an R-Nav segment is assigned and in use, the multi-tone request is denied in "canned" voice. Since the interlocked replies to all solicitations and airway assignments in their local area are monitored by the pilots, the ground and other aircraft actions are clear (in, of course, low-density airways created by the VORMEGA technique).

Next, once the airways segment is authorized, the aircraft occupancy is assumed until the next waypoint is reached. With the capacity of literally hundreds of parallel airways possible with the basic coordinates and geometrics of a VLF system, airways as closely spaced as VORTAC R-Nav airways are readily possible. For an aircraft to simply request an adjacent segment (to the right, left, above, or below the one occupied), he pushes the data tone buttons. Upon being accepted, he then utilizes the airway.

Thus, a pilot could take off, adjust his display to the first waypoint, and upon reaching it, push three buttons in rapid sequence (as in touch-tone dialing), taking about a second, and receive in the next few seconds voice permission to move from the current waypoint along the airway to the next waypoint. In coverage of a given VHF facility, many airways and many altitudes would be codified so that the tone-data would identify the desired airway segment automatically, and the "canned" voice reply would confirm commitment and assignment.

The pilot could then continue through a series of waypoints, being assured of his single airway occupancy between specific waypoints by the above low-cost tone-data means. He arrives at his destination normally without any direct human controller monitoring or any radar-vectoring. Figure 32 illustrates these basic Broadcast Control principles.

TABLE III

COMMUNICATIONS IN BROADCAST CONTROL
USING INTEGRATED VOR/OMEGA SYSTEMS

FUNCTION	PILOT ACTION
Set Omega Diurnal	a. On ground at takeoff b. Listen to VOR voice channels c. Request with tone-data
Request Airway Use	Pilot activates 3 or 4 pushbuttons of the $100 microphone input tone-data unit from his airway chart
Codes Available	3 tones - 4,096 4 tones - 65,536 VHF channels - about 40 Adequate codes in 1 to 2 second "burst"
Assessment of Interlock of Requested Airway	Listens to voice confirming request for 1 of possibly 100 airways within a total of 6 to 8 seconds
Pilot Monitoring of Broadcast Control	Hears all other assignments to other pilots in his area as simplex VHF is used
ATC Density	Low since all jets and high-performance aircraft use VORTAC R-Nav and radar/ computers, counters
Request Approach to Small Airport Without Tower Personnel	Tone code noted on chart is used, and voice (canned) approval is given by interlocked system if airspace is free
Broadcast ATC Integration with NAS	Airspace assignments are in simple interlocked form available to a center if desired
Channels Used	VOR voice mostly and some "Unicom"
Waypoint Clearance	Pilot requests by tone data, receives a reply by "auto" voice and, once executed, clears by tone data to the next waypoint

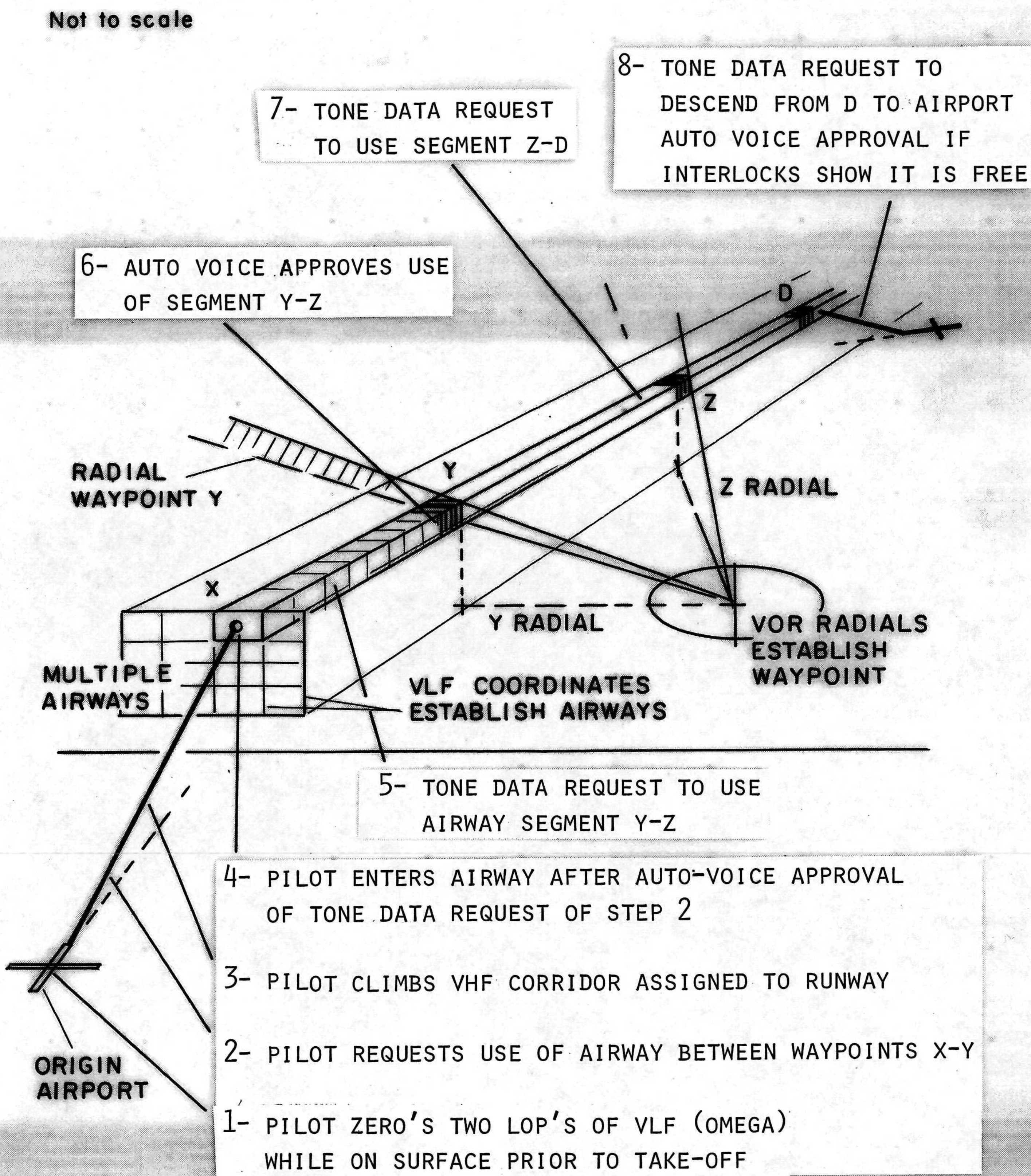


FIGURE 32 BROADCAST CONTROL USE OF VLF/VOR AIRWAYS BY LIGHT GENERAL AVIATION AIRCRAFT POPULATION

In dense terminal areas the controllers will organize priorities since the complexities of feeding, say, parallel runways from 6 airway directions and 10 latitudes, create some 120 possibilities. Contrary to this, in a general aviation report with a single runway and low-density dispersed air traffic, no such controller intervention is needed. This use of enormous amounts of new airspace that become available with VLF airways lowers density of traffic enormously, adds capacity, and thus allows these greatly simplified concepts of Broadcast Control to be realized. The ground communications complexity is very low, using production units of the Bell system tone-data decoders, interlocks, and canned messages.

B. DIURNAL VLF DATA FROM COMMUNICATIONS

Diurnal changes must be inserted occasionally in the VLF use of airways structures, just like one has to insert new bearings and select new frequencies in VOR. However, the communication job of assuring all pilots at all times of the local diurnal setting (for differential Omega) is essential to this new concept of Broadcast Control based on "wide-area" navigation. Here the marriage of VOR and Omega is obvious. The pilot can set his runway position in VLF coordinates very easily at takeoff, essentially making the first diurnal correction. When he then requests an airway segment, this can be solicited from a VOR station.

In addition to replying to this specific aircraft (and locking out the airway to other requests), the VOR automated voice response can also communicate to the pilot by "canned" voice the exact diurnal setting in that area. Since VHF signals travel only for a given (line-of-sight) distance, this will confine this data to an area possibly about 50 miles surrounding that VOR station, so that a diurnal correction of the same VLF coordinates in California is not confused with the diurnal corrections in New York, even though both aircraft are receiving the same VLF radio navigation transmissions. Even though 3,000 miles apart (one of the enormous advantages of VLF), each aircraft receives from the VHF Unicom or VOR the correction specified only for that area.

Figure 33 suggests the elements in this air-ground-air communications function used in Broadcast Control.

Next, communications should also supply a recent barometric altimeter setting, because the use of all airways is so dependent on vertical separation data. It is obvious that data for baro-settings and diurnal settings can be sent on the VOR voice channel at a much lower rate than the ATC Broadcast Control data that requires some form of closed-loop acknowledgment to the pilot. By avoiding ground-vectoring and using VORMEGA R-Nav, the ground to air communications load is very low. In Broadcast Control, mostly "go-no-go" answers are needed to tone data requests for three-dimensional airspace. Since so many additional flexible airways will be created with VORMEGA, nearly all replies will be "go."

If, for example, airways are spaced every 5 miles based on (1) VLF coverage and (2) general aviation use of 10 altitudes, then within the VHF COM coverage might be 100 airways that can be numbered 1 to 100. Next, we might have waypoints on each airway every 10 to 20 miles assigned the letters "A" through "K," as in Figure 34. In this manner, a maximum of 1,000 codes of the 4,096 codes available (3 bursts of the 4 X 4 dual-tone system) are utilized. Possible use of the remaining 3,000 codes would allow expansion of waypoints, ATC requests, approach tracks, etc. Since all VOR channels must be "clear," this would mean that the adjacent VOR stations would each provide another 1,000-segment capacity, or we can now use this for control of airspace separated from the first VOR. Thus, RF channels could further increase this potential communications capacity (nationally) by about another 40 times.

Since it takes a general aviation aircraft following these airways about 4 to 5 minutes to fly 10 miles to the next nearest waypoint (see Figure 34), we must consider the most frequent communication cycle for a given aircraft. The air-to-ground tone-data solicitation and the ground-to-air (automatic) "canned" voice (confirmed) reply takes about 6 to 7 seconds; then, an aircraft's maximum utilization (reporting and requesting at every waypoint) of the channel would be about 2 to 3 percent of the time,

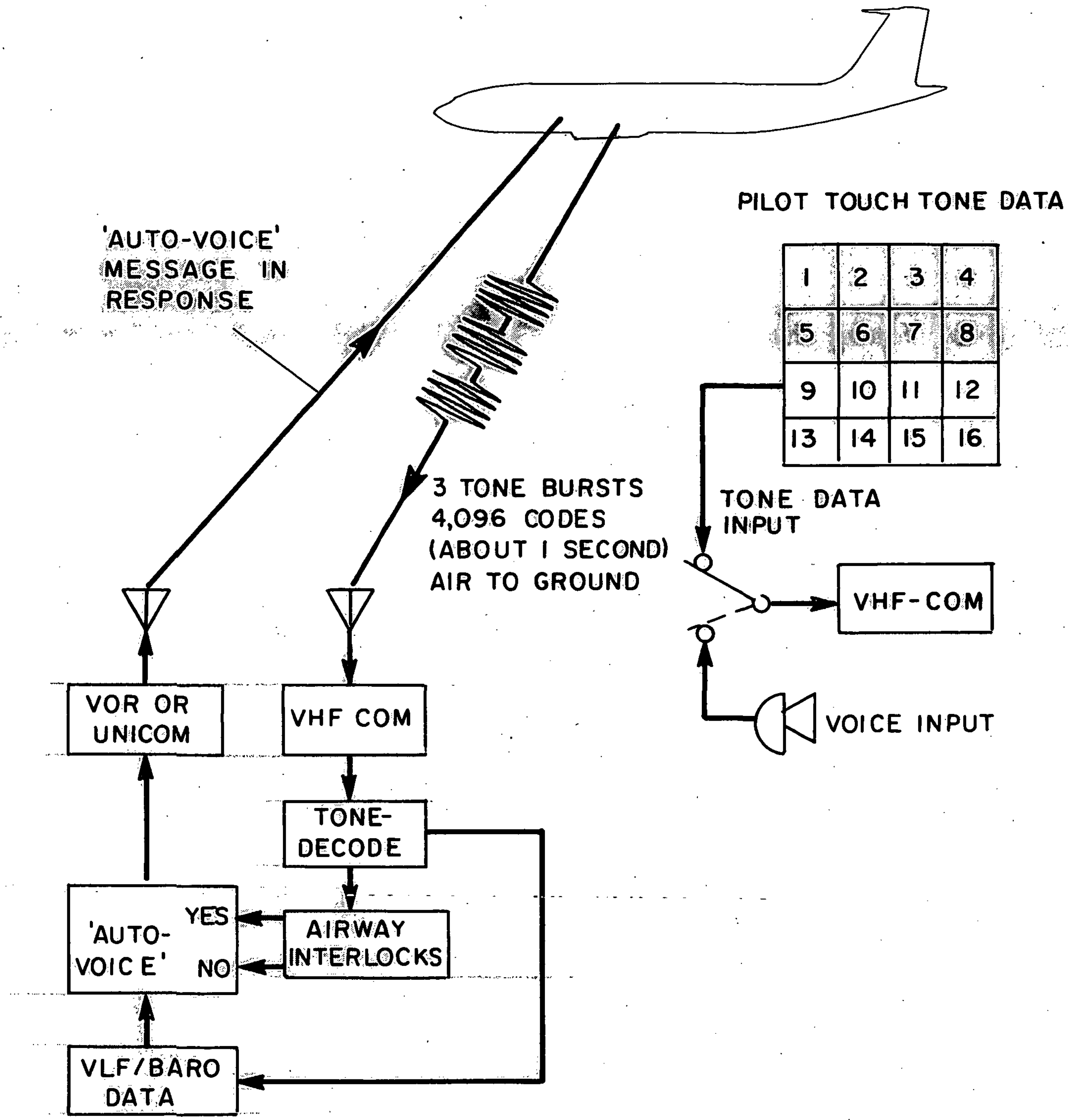
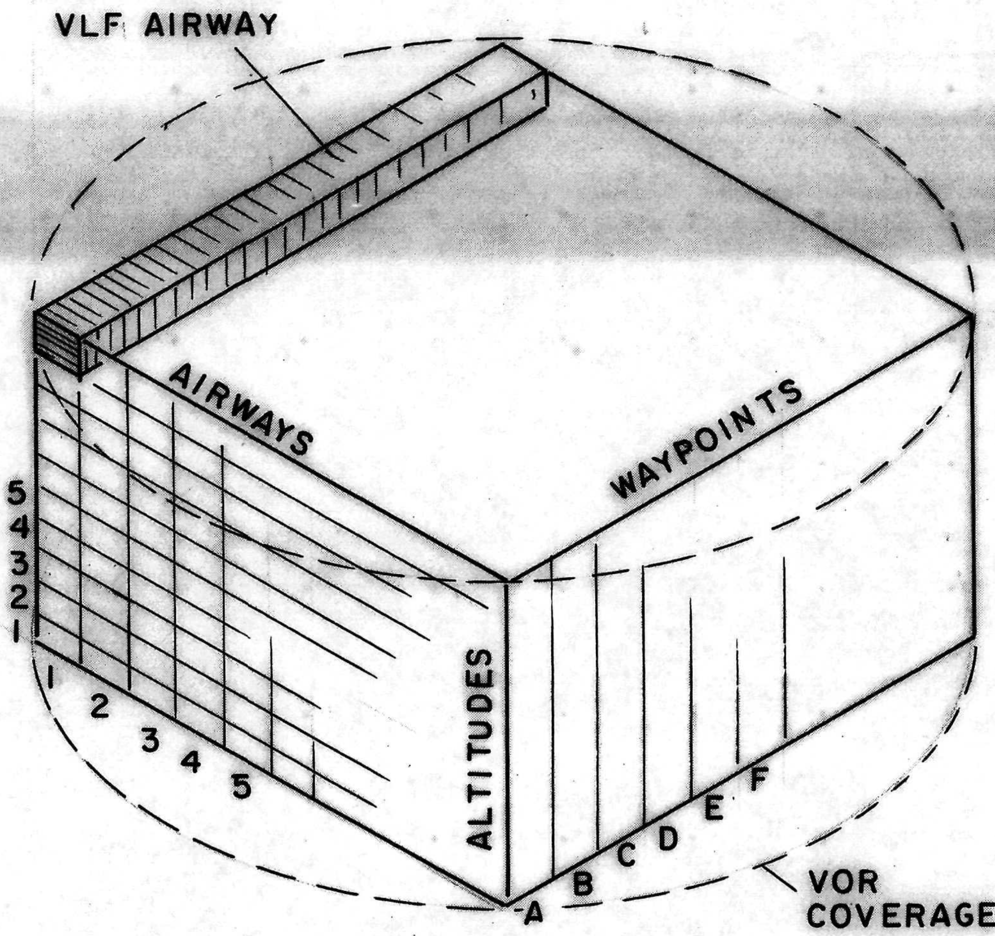


FIGURE 33 AIR-GROUND AND GROUND-AIR COMMUNICATION LINK FOR BROADCAST CONTROL OF ABOUT 85 PERCENT OF GENERAL AVIATION

34



ASSUMING 10 ALTITUDES AND 10 PARALLEL VLF AIRWAYS WE HAVE A TOTAL OF 100 AIRWAYS IN AN AREA ABOUT 100 X 100 MILES, WITH 10 WAYPOINTS ON EACH AIRWAY, WE HAVE A TOTAL OF 1,000 DISCRETE AIRWAY SEGMENTS THAT CAN BE ALLOCATED IN BROADCAST CONTROL USING 3 BURSTS OF BTL TONE DATA FROM THE AIRCRAFT TO REQUEST THE DESIRED AIRWAY SEGMENT (TIME REQUIRED 1 SECOND)

FIGURE 34 1,000 DISCRETE AIRWAY SEGMENTS OF BROADCAST CONTROL

thus allowing other aircraft to use it 97 to 98 percent of the time.

Since it is likely that the pilot will usually ask for a long segment (say 20 to 50 miles), and it can be approved because of our very large airway capacity and the dispersion of traffic, the communications load is reduced considerably, possibly making it suitable for serving about 30 to 50 aircraft per VOR voice channel. It is also possible to assign a "Unicom" channel to this Broadcast Control service if the traffic warrants.

However, if, say, in a 100 X 100 mile area one finds typically 10 to 15 VOR stations, the Broadcast Control communications capability would be (for this 100 X 100 mile area) as high as 300 to 400 general aviation aircraft all simultaneously using Broadcast Control. This is one of the major merits of Broadcast Control in Area-Nav--a large reduction in air-ground communications. All "VFR" flying would utilize this Broadcast Control concept, since the concept in essence gives freedom of movement. It also supplies to all users (by listening to communication assignments) identified airspace occupancy data, so that most of the many "VFR" mid-air collisions can be avoided.

The very fact that VLF is used to generate hundreds of new airways for general aviation with routings to thousands of outlying airports will assure the authorities that a specific aircraft is not violating the airspace of others. This violation often occurs in VFR rules by an error on the pilot's part--either not knowing where he is, not knowing the three-dimensional limits of high-density airspace, or simply attempting VFR flight under questionable visibility.

C. BROADCAST CONTROL COMMUNICATIONS COSTS MUST BE LOW

Thus, it is evident that in addition to the VORMEGA navigational coordinates that are a basic part of the Broadcast Control of air traffic, a communications link must also be designed for Broadcast Control needs. Fortunately, these needs are much less than high-density Close Control concepts, allowing low-cost innovative techniques. The total costs for Broadcast Control to appeal to general aviation must be considerably below current

costs of VORTAC R-Nav equipments and data links such as "DABS." Assuming that VHF-COM is very widely used, the total added communications costs for Broadcast Control should be about $100 by adding the 4 X 4 pushbutton tone-data board (one of 16 tones for each activation of a button representing a digit). This board is small, light, transistorized, and can be added to any cockpit. The microphone input takes the data tones, since they are all inside the band pass of voice frequencies*. The exact tones received extensive tests and were selected for this bandwidth and to be immune from voice jamming (see references 34 and 35). Table IV lists the suggested uses of Bell's 4 X 4 dual-tone data for air-to-ground communications.

D. LONGITUDINAL SEPARATION IN BROADCAST CONTROL

The means for providing many new airways with the VLF coordinates have been discussed. These are effectively new airways making use of airspace for air traffic control purposes that would otherwise be unavailable. The contiguous nature of the VLF coordinates and their uniformity and universality of coverage avoids large gaps in coverage and geometric convergence typical of VOR and VORTAC that denies much airspace. The marriage of VOR and Omega is proposed, because of the great number of advantages, particularly to general aviation users of the national airspace and, therefore, the urgent need for extremely low-cost "area-navigation" and low-cost Broadcast control.

Thus, the pilot can request with a 3 to 4 tone-data "burst" that takes about 1 second the availability of one of possibly 1,000 airway segments or combinations of segments defined in three dimensions. Waypoints on the airways can be assigned by traffic density to reduce communications and pilot workload. For example, an airway might have 3 waypoints; if it is in use, possibly only the airway to the first waypoint is assigned. If the airway is unused, all the waypoints (a series of airway segments) can be assigned by simply blocking out that airway for a time and satisfying the next request for it with one of the immediately

* Typically they are frequencies of 697, 770, 852, 941, 1209, 1336, 1477, and 1633 Hz.

TABLE IV

SUGGESTED USES FOR BELL SYSTEM'S "4 X 4" DUAL-TONE DATA FOR AIR-TO-GROUND COMMUNICATIONS

1. Investigate it as a major element in Broadcast Control concepts to avoid ground personnel intervention.
2. Request airway use by tone code (up to about 160,000 codes).
3. Does not prevent voice use of VHF/COM, but speeds up transmission and data handling in Broadcast Control.
4. Reception on the ground is automatic and can key automatic voice response for specified airway approval, etc.
5. Retains voice as ATC reply on ground-to-air link, voiding the need for costly airborne decoding equipments ("coding" is usually low in cost, and "decoding" is usually high in cost).
6. Pilot requests airport lights to be turned on.
7. Pilot can request automated barometric data.
8. Pilot requests approach to unattended airport (no tower) via FSS and ground interlocks.
9. Can "encode" manually or automatically any airborne data for air-to-ground transmission such as identity, position, altitude, etc.
10. Pilot requests clearance on airway to given waypoint with approval via voice response from ground unit, without controller interventions in low-density ATC areas.
11. A low-cost means of bringing Broadcast Control and hundreds of new airways to general aviation's lowest price range.
12. Provide waypoint-to-waypoint clearances on specified airways.
13. Air-to-air position reports monitored by pilots listening to a common voice channel.
14. Emergency codes and many other possibilities of unique messages.
15. Semi-automated request for VHF bearing data (VHF/ADF).
16. Low-cost, semi-automated tower functions at non-personnel towers.
17. Can add minimum "discipline" needed for Broadcast Control of about 80 percent of general aviation aircraft and approach discipline to about 10,000 airports used by general aviation without towers.

adjacent airways. In low-density traffic typical of airspace removed from jetports and jet airways, this implies that nearly every flight has a "private" airway, since VORMEGA will have such enormous airway capacity as compared with today's airway capacity. However, the question arises of how spacing along the assigned airway is maintained in this concept of Broadcast Control.

As is done today, all pilots listen to all air-to-ground and ground-to-air voice communications on the VHF channels they are assigned for ATC. This gives each pilot a mental picture of the traffic about him and what the intent of the traffic is. Enormous intelligence concerning adjacent aircraft, ATC plans, flow rates, errors, emergencies, etc., can all be gained by simply listening to the air-ground voice data used in ATC.

In monitoring air-ground VHF communications, it is evident that the pilots are excellent judges of the actions of controllers and pilots of other aircraft. A controller must be concerned with perhaps 6 to 10 aircraft under his responsibility, but the pilot is concerned only with his own aircraft's safety, expedition, and well being, as it is the only one he controls. The pilot views the ATC process from his coordinates in the system (say, an airway, altitude and fix), catching any errors controllers or other pilots make in altitude assignments, estimated times to clear fixes, etc.

Retention of voice in any ATC process is essential to permit even the minimum involvement of the pilot. Otherwise, he must take with blind faith instructions (good or bad) from the ground. Soon, this trend will be worse because of the automation of SSR data and DABS, both of which tend to further remove the pilot from the essential involvement he now has with voice data experience.

In Broadcast Control using Area-Nav, we hope to reverse this trend bringing the pilot more into the ATC loop, creating major economic savings, greater efficiency, and safety in the ATC process.

Thus, rather than deny the pilot the use and reduce the importance of voice data, we would increase the emphasis on voice data in Broadcast Control as being the most versatile, low-cost,

ground-to-air data transfer system that exists. Voice does not need additional data-link receivers, annunciator displays of "commands," etc., for realizing the benefits of Broadcast Control. This is true primarily because Broadcast Control, though using voice data, uses much less ground-to-air communications, while Close Control, as in DABS, uses more and more, saturating voice capabilities and forcing new capacity by digital data links that cannot be "listened" to by others or cannot be interpreted directly without a costly decoder. In a few words, this is the dilemma in ATC that faces us in the 1970's and 1980's.

The pilot in the Broadcast Control concept, of course, hears the voice assignments from the ground, so that if he is located in a given airway, he would hear the assignment of adjacent airspace above, below, ahead, and behind him. Assignments to a given aircraft provide both its location and identity by voice. For example, the auto voice would say, "Aircraft XYZ is assigned airway 77 to waypoint L." Since this is heard on the one VHF channel assigned to that airway and adjacent airways (such as a Unicom or the VOR voice channel), an added step in the selection process takes place. Another pilot, who may be between fixes M and N on airway 77, hears the assignment to waypoint L and now knows that another aircraft is on his airway but separated from him by the distance between the two fixes, L and M. Unidirectional airway travel prevails as in the current "rules of the air," which have been established for many years.

Thus, to repeat, it is possible for the pilot (by voice monitoring) to create a mental picture of the airspace assignments and occupancy by other aircraft since uniformity of airways is already possible with VLF transmission. As he or the other pilot subsequently arrive at their waypoints and request clearance through them, the two pilots can monitor this fact. It is also possible in the Broadcast Control technique to add some form of air-to-air proximity control as a reassurance that the supposedly adequate separation, using waypoints, is being maintained. One such system is to make use of the ATC transponders that are becoming nearly universal in their airborne applications. The aircraft transponder "listens" to the pulse replies of the aircraft near

him, and by a filtering process of common-azimuth, common-time-differences and co-altitude decoding of the beacon pulse coded replies, it is possible to obtain an air-to-air measurement to aid in "proximity control" (see reference 36).

Thus, the pilot would obtain from his monitoring of the voice ATC data used to assign the airways waypoints and (if available in SSR coverage) an independent measure of the proximity of other aircraft at his altitude--adequate assurance that Broadcast Control was working properly. If the pilot is aware from voice data that the next block of his (airway) airspace is occupied, this will alert him to keep a closer watch on his proximity control indicator. Even though blocks for general aviation use would be a minimum of about 10 miles and usually longer (say, up to 50 miles long depending on ATC needs in a given locality), it would be reassuring to the pilots using Broadcast Control with little ground personnel intervention that another aircraft for some reason is not too near the block limits or has somehow made a cockpit error--something all systems are susceptible to, and must therefore have some form of redundancy.

E. MONITORING OF BROADCAST-CONTROLLED AIR TRAFFIC

In Low-traffic-density areas where towers are not available and ATC centers do not serve, we can offer to the tens of thousands of general aviation aircraft an ATC service that fits their needs economically, technically, operationally, and is consistent with regulatory practices. The present deficiencies--(1) wasteful use of airspace by VOR airways which also causes (2) local congestion when aircraft use what airspace is adequately defined by VOR--are both overcome by a "total coverage" system of VLF/VOR, such as VORMEGA.

The known weaknesses of VLF-Omega can be overcome either by integrating the Broadcast Control concepts with VOR (in a VORMEGA), or ultimately using a new VLF system, custom engineered, tested, and installed solely for the contiguous geographic area of the United States. Such a plan, including VORTAC R-Nav and Omega R-Nav, allows back-ups by separate use of VOR in case of Omega failure, and use of Omega where VOR has failed or is

deficient, such as at low altitudes, on the airport surface, mountainous regions, and at hundreds of remote airports. Other comparisons and relationships are shown in Table V.

Rather than adding a burden on the SSR monitoring at towers and centers of traffic utilizing Broadcast Control, we will use self-monitoring and self-discipline techniques by the users. This new ATC capacity will at least double the potential airways, giving more than enough defined airspace to general aviation and, most importantly, arranging the airways to go to thousands of small airports rather than to the centralized jetports and cities where the VORTAC station coverage is most dense (see Figure 35).

We will use a very-low-cost air-to-ground VHF tone data link to request use of this new airspace (not the VORTAC Area-Nav airspace which is reserved for jets primarily). This "segregates" the air traffic geographically and vertically in accordance with ability to pay, speed, climb-descend needs, cruise altitudes, origins-destinations, and importance of the missions. This newly segregated system would utilize Broadcast Control methods for establishing and authorizing flights along the vast new airways structure created by the combining of VOR/Omega concepts. The costs are so low as to be acceptable to the lowest economic layer of general aviation (the nearly 200,000 single-engine aircraft expected by 1980-1990, for example). We will rely on Omega as a back-up for VOR where its signals are off the air or limited by propagation, and use VOR as a back-up for Omega in case of signal disturbances; thus, when the two independent LOP systems are used for Broadcast Control, "escape" tracks exist. Either holding a few minutes for the signal to return or flying to a safe destination are options open to the pilot in this concept. One cannot do this with VORTAC because DME is not a linear LOP, but a circle; it is also an LOP that is uninstrumented for track following and thus cannot be used for these and other limitations as a back-up for VOR failures. Consequently, as VORTAC R-Nav progresses, the costs for even "basics" will be doubled for this type of service, since dual VOR and dual DME will be essential to creating an Area-Nav LOP with some form of a back-up. Omega can create its own multiple LOP's once diurnal corrections are applied.

TABLE V

COMPARISON OF VORTAC R-NAV AND VOR/OMEGA R-NAV

ATC FACTOR	VORTAC R-NAV	VOR/OMEGA R-NAV
Type user	Fast, high-flying airliners and jets (about ten thousand)	Slow, low-flying, 85 percent of general aviation aircraft, or about 150,000 aircraft
Inputs to the ATC process	VOR; DME; 3-dimensional barometric altimeter. Creates airways on new display that are horizontal, vertical, or both	VOR receiver now in most general aviation aircraft; add only an Omega receiver and an R-L indicator for airway performance
Location of R-Nav airways	Between jetports	Parallel to VORTAC airways and below them and leading to 10,000 general aviation airports
Costs	Very high, but commensurate with airline use and jet aircraft costs; minimum cost estimated by some at $15,000	Within reach of possibly 80 percent of general aviation aircraft that cannot afford VORTAC R-Nav (add about 1 to 2 thousand dollars)
Type of control	"Close Control" such as radar-vectoring or DABS, requiring computers and many ground personnel	"Broadcast Control" with major pilot participation and few ground personnel
Use of airspace	Adds somewhat to the capacity of the VOR airways but serves same high-density areas as now	Creates possibly 2 to 3 times (new) amounts of non-conflicting airways, mostly suited to general aviation and STOL vehicles in low-density areas
Back-ups	Dual VOR and DME are needed as DME is not an LOP system. SSR transponder and radar vectoring also available	VOR backs up Omega, and Omega backs up VOR, as both are lateral LOP systems, using simple coordinates
Three-dimensional requirements	Spherical coordinates with randomly located sources must be tied together and corrected in three dimensions	VLF and VOR are "planar" LOP coordinates when used in Broadcast Control, avoiding three-dimensional corrections

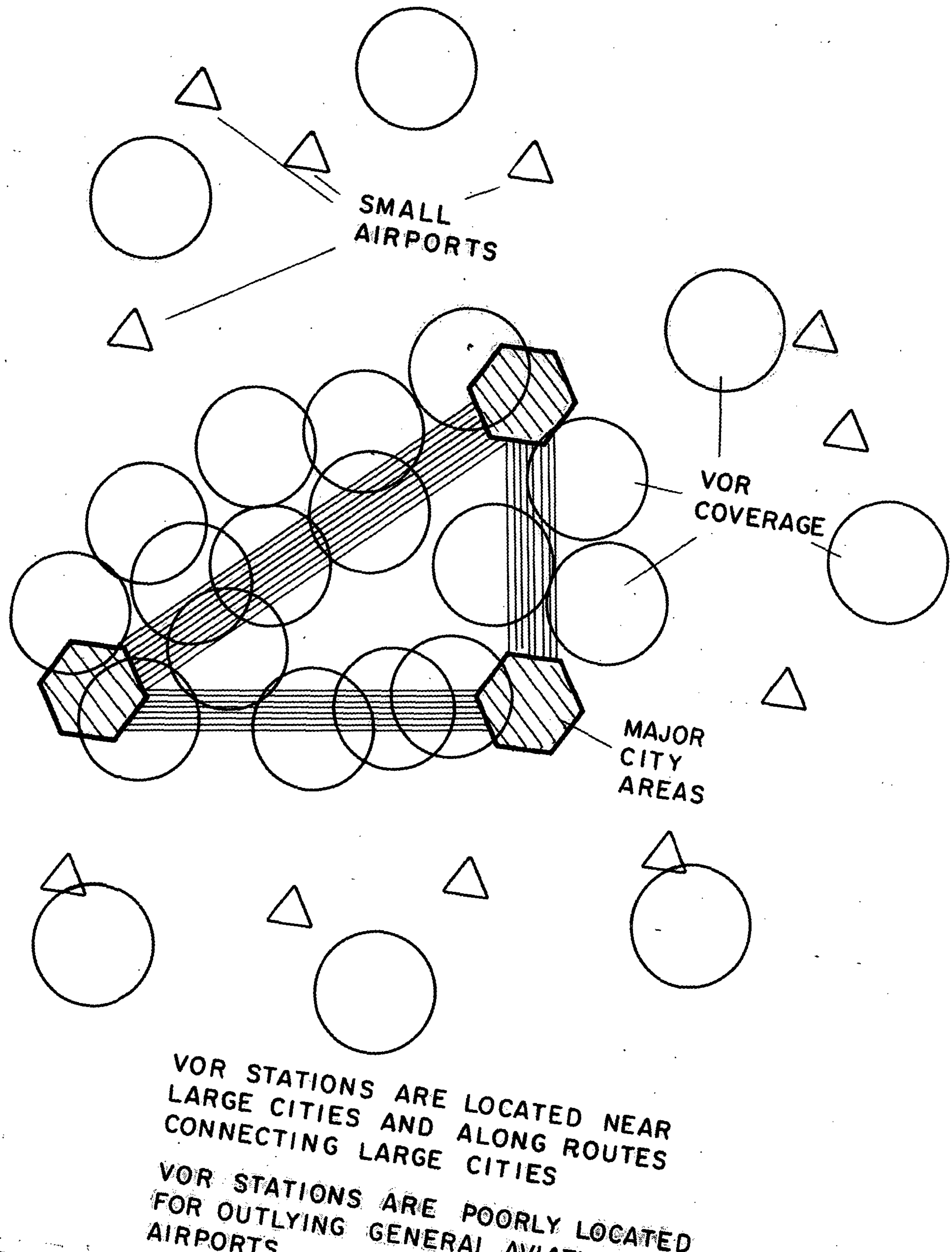


FIGURE 35 VOR STATIONS SERVE MOSTLY DENSE TRAFFIC

Thus, not only is the pilot assured of the reliability of airway coordinates in Broadcast Control, but he can follow them by cockpit requests using his tone data input unit. He then listens to the VHF channel to receive his own approvals (addressed to him by time correlation or actual identity). Just as important, he also hears the assignments to other pilots, so that if any conflicts occur, the pilots can then use direct air-to-air voice communications to resolve the conflict without intervention of ATC personnel from the ground.

This concept of VFR and IFR airways is appealing to low-density ATC areas, where radar centers or towers are not likely to be available. Even though VHF and SSR signals exist in the airspace, the authorized airways are but a small part of this propagationally covered area because of the serious "geometric" constraints noted previously. Propagational coverage of an area or volume with radio signals and authorized airways is an entirely separate matter. One is engineering, and the other is operational. Station location or its limited coordinates and LOP's often deny much use of the airspace with airways, even though it is actually covered with radio signals. All airways converging to a single point create high-density traffic only at one point, while most other points are not served at all, with nearly zero traffic.

Broadcast Control tends to add the type of discipline that pilots can cope with and removes much of the current fear of "VFR" flight where uncontrolled traffic can mix with controlled traffic--or even worse, in VFR conditions of 3 to 4 miles of visibility when it has been shown to be almost impossible to visually detect a potential collision in time to avoid it. So-called "controlled VFR" flight or "VFR Airways" assures all parties, controlled and uncontrolled, that a national standard on discipline and the use of airspace exists in Broadcast Control systems.

Airspace can be available by a simple, in-flight, cockpit request; however, once assigned it is known to others. Of course, the general aviation Broadcast Control traffic data flowing to and from the ground (with little controller intervention) is also fed by telephone lines to a centralized point, such as a center or Flight Service Station if it is desired for processing

purposes or monitoring. However, this is for monitoring, not for control functions. It is also useful for recording traffic statistics or for emergency search and rescue functions if any aircraft is lost. This monitoring in Broadcast Control concepts is quite a different concept from radar-vectoring, where so much manpower, high loads on communications, and costly, complex (and potentially unreliable) ground equipments are involved, as in Close Control techniques.

Table VI gives a summary of the principal features of Broadcast Control of general aviation air traffic based on the use of VORMEGA and VHF-COM.

TABLE VI

SUMMARY OF PRINCIPAL FEATURES OF BROADCAST CONTROL OF GENERAL AVIATION AIR TRAFFIC BASED ON THE USE OF VORMEGA AND VHF-COM

1. Thousands of new VLF airways and approaches to small airports can be authorized with waypoints defined by both VLF and VOR radial crossings of the airway.

2. This provides enormous new airway capacity, particularly for low-density airways well suited to the widely dispersed general aviation airports.

3. Each flight can now be assured of (1) optimized routing from this new capacity of airways and (2) assignment of a long airway segment; this greatly reduces air-to-ground and ground-to-air communications. Pilot workload is lower.

4. The pilot uses tones in the voice band as inputs to his communications transmitter to request from a 4,000-code selection a given airway segment in three dimensions and receives acknowledgments from ground-based tone decoders, interlocks, and auto-voice.

5. Human voice is the ground-to-air data transmission system. Mostly, the Bell tone data system is used in the air-to-ground link with voice also being available. Tone data is immune to voice interference.

6. Pilot proceeds to use airspace he desires. If occasionally his first choice is already occupied, an adjacent lane airway can be approved from the large airway capacity.

7. Pilot execution of airway following (Area-Nav) suited to any geometric shape (direction, segmented, etc.) greatly reduces communications load. No radar surveillance is needed, since ground interlocks prevent assignment of same airways segment to two aircraft at the same time.

8. Pilot may proceed without intervention of ground (ATC personnel) using the "closed-loop" of Broadcast Control via the tone-data solicitation and auto-voice reply from the ground interlock system that can be a part of the flight service station concept.

9. Assuming airlines use VORTAC R-Nav on dense air routes between major city pairs, Broadcast Control assures all pilots that general aviation and airline traffic remain separated and controlled under all conditions.

IX. SUGGESTED R AND D PROGRAM

It is suggested that some of the available low-cost Omega receivers now becoming available be used for some operational flight testing of the many concepts and procedures that constitute a Broadcast Control ATC system for general aviation. These include:

1. Test the concept of a 400-foot/1-NM, non-precision approach to every runway in the nation.
2. Determine the difficulty of always having the VLF navigational LOP aligned with the extended runway centerline for approach to avoid "circling."
3. Determine from flight tests the optimum use of "crossing-LOP's" from those inherently available in the Omega system and, if a suitable "distance to threshold" (DME) is available--as well as the extended runway centerline non-precision approach guidance tested in (2).
4. Tests of the pilot's use of simple barometric data and the VLF data to "construct" a non-precision vertical path to the runway threshold and centerline. Flight test available instrumentation that has been modified for this purpose.
5. Acquire and test the tone data-link of BTL with a 4,096 code structure at first to determine whether the pilot ATC solicitation "burst" can be completed in 1 second and whether it is reliable.
6. Acquire a BTL tone data decoder and connect it to the output of a VHF-COM (Unicom) ground receiver to determine the reliability of VHF decoding and the ability to reject voice interference of codes on the same channel.
7. Confer with the Bell Laboratories staff on their extensive "voice-immunity" tests.
8. Test "auto-voice" available from Bell Systems that will provide a voice reply to the pilot's solicitation utilizing coded inputs for airway requests, diurnal check, barometric data, automated-tower clearances, and ability to relate interlocked conditions of airway assignments essential to Broadcast-ATC concepts.

9. Configure a basic Broadcast Control system consisting of pilot tone data solicitation, ground reception of tone data, decoding and assignment of a specified segment of a specified airway without human intervention on the ground.
10. Test the combination of VLF and VOR along the lines of a "VORMEGA" system.

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